Tensor Polarization: A New Window into Nuclear Structure

Dr. Elena Long

SPIN 2018

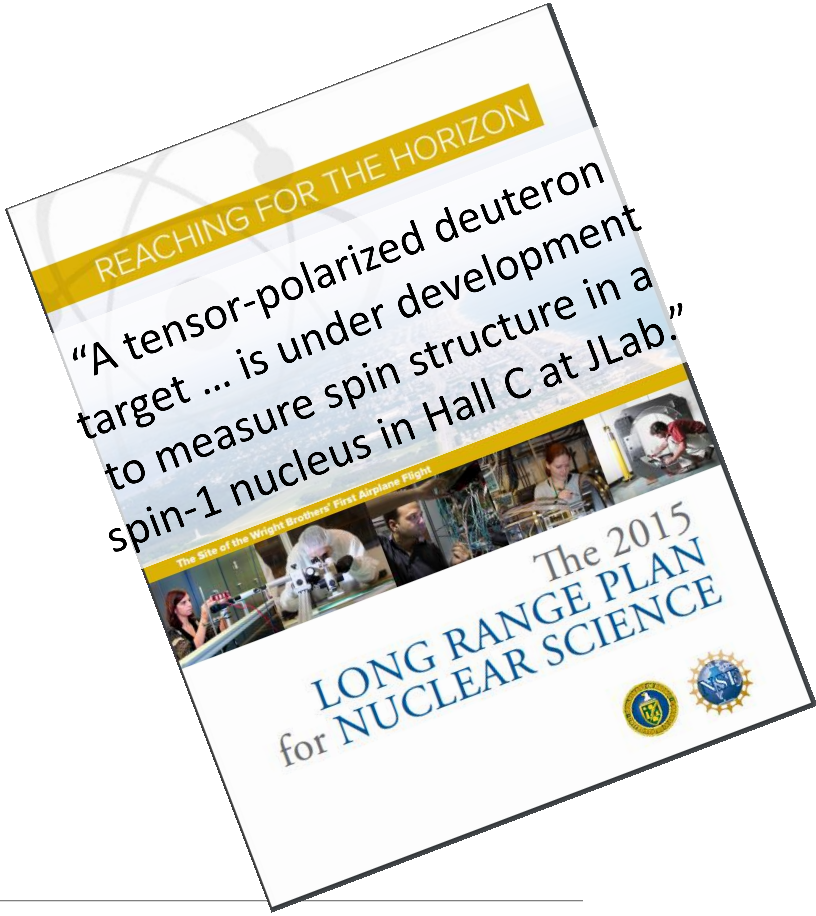
University of Ferrara

September 8th, 2018

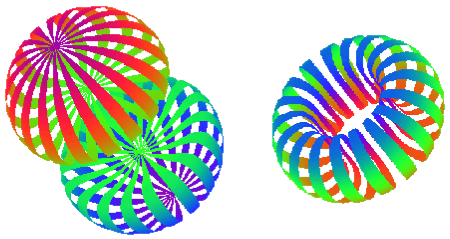
University of New Hampshire

Long Lab

Where Do We Go From Here?



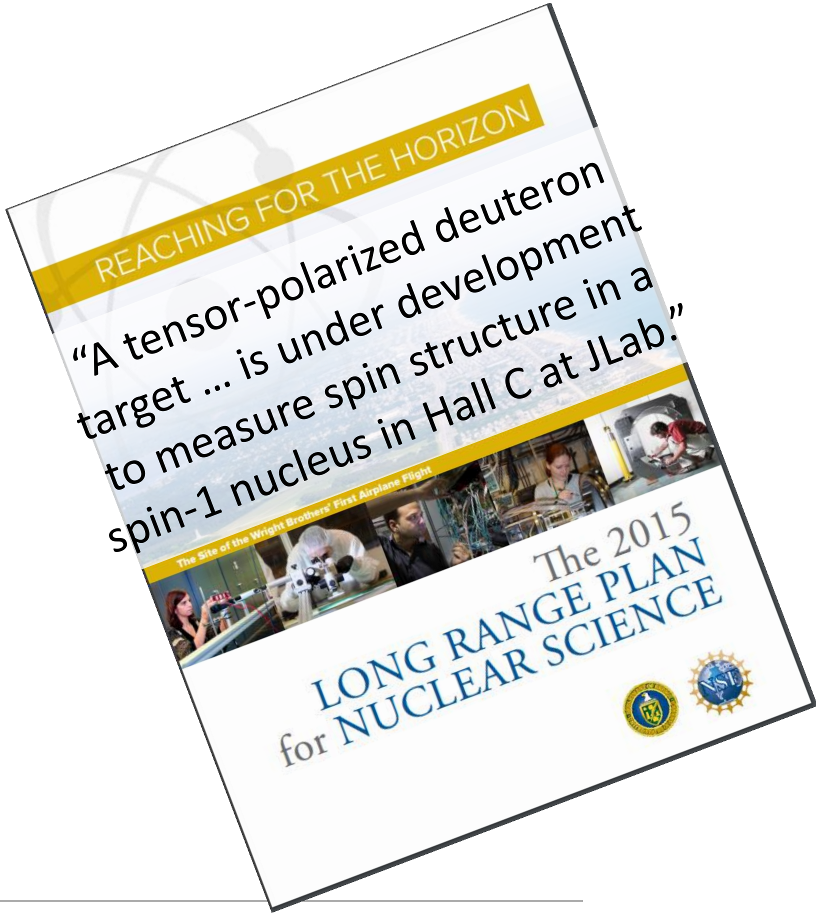
New Degree of Freedom: Tensor Polarization



"The proton, **deuteron**, and α particle are most interesting to study because they are among the simplest nuclear structures."

RW McAllister, R Hofstadter, Phys.Rev. **102** 851 (1956)

Shout out to Eva Weiner, Mother of Modern Nuclear Physics Targets. She built Hofstadter’s Nobel Prize winning target but tragically died in a 1953 car crash.



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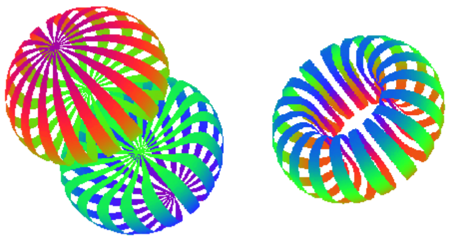

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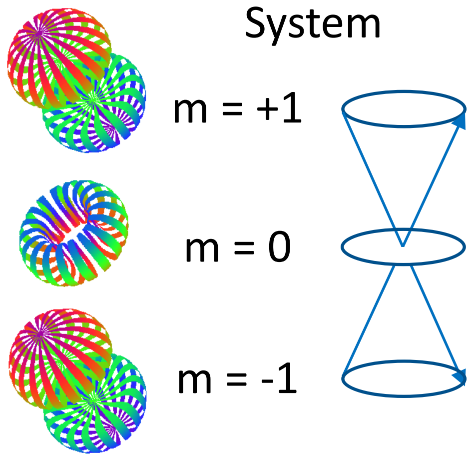
What is Tensor Polarization?

Spin-1
System



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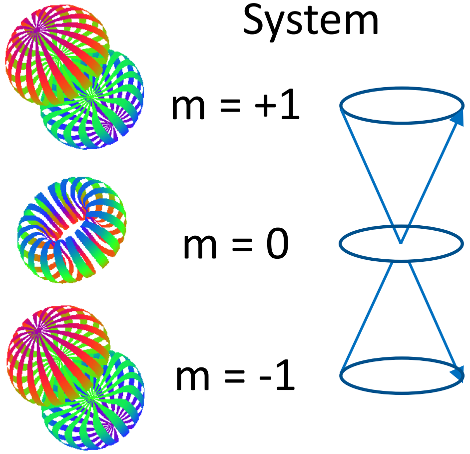

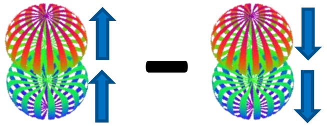

“Normal” Polarization:
Vector $P_z = p_+ - p_-$

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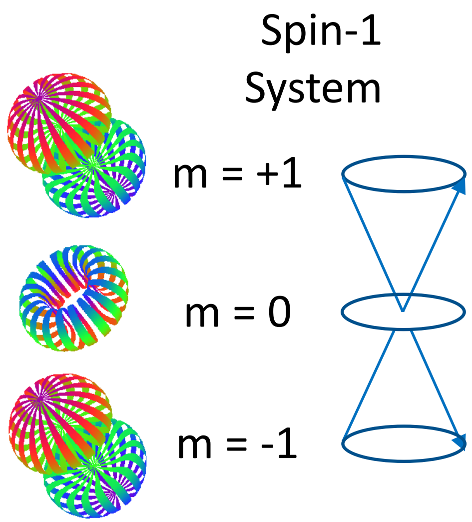

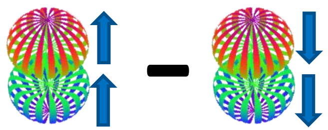

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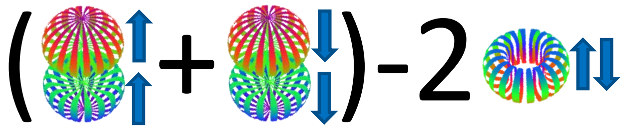

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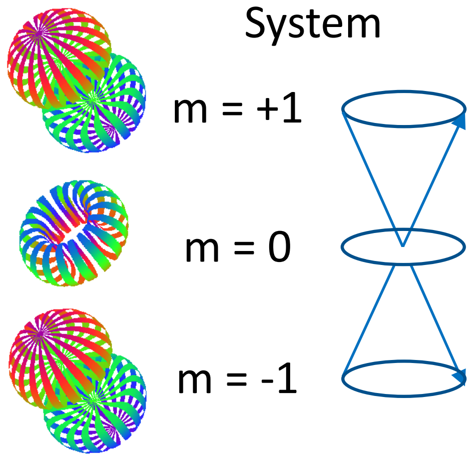

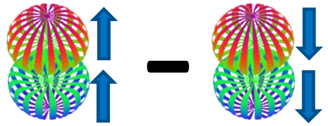

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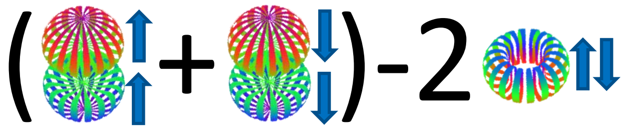

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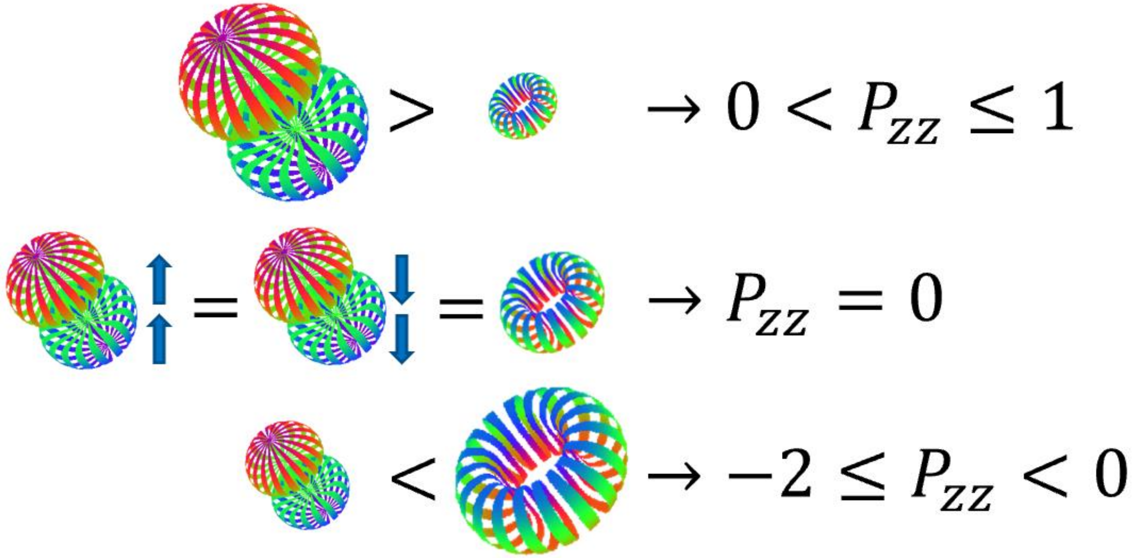

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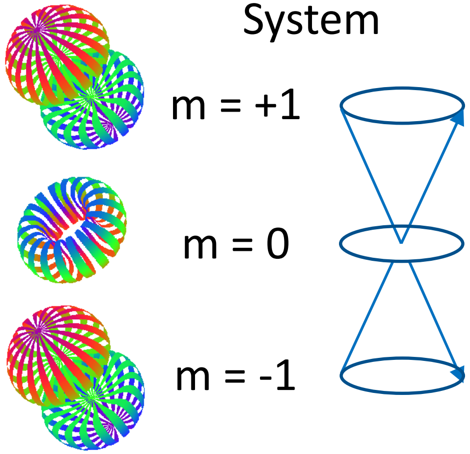
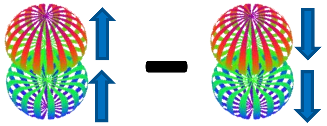
What is Tensor Polarization?

A high-luminosity tensor-polarized target has promise as a **novel probe of nuclear physics**

Spin-1 System





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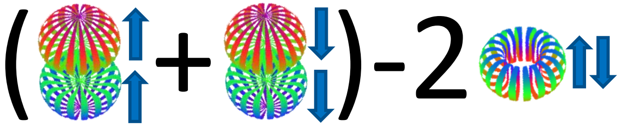

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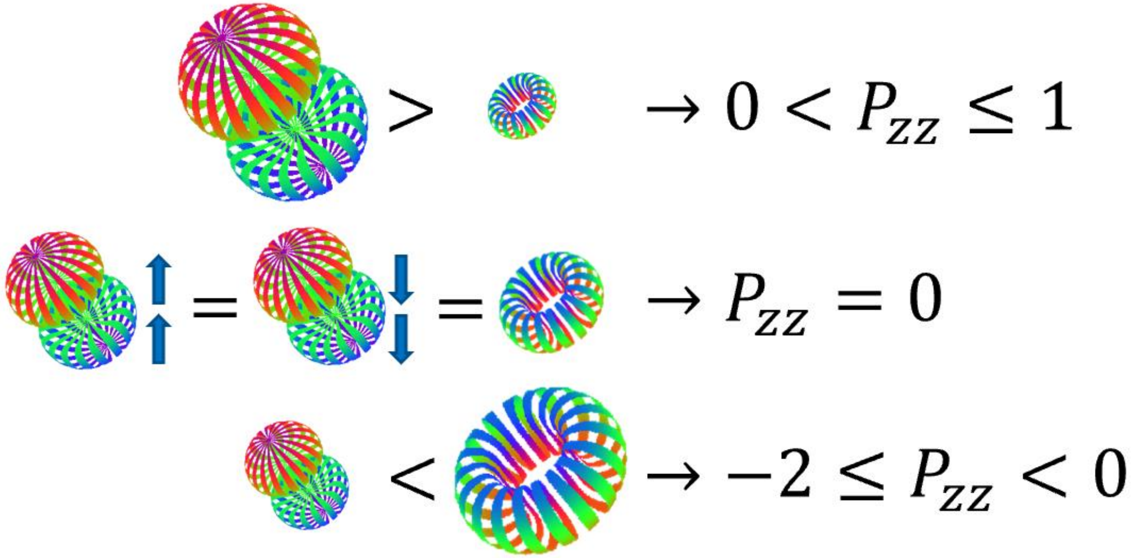

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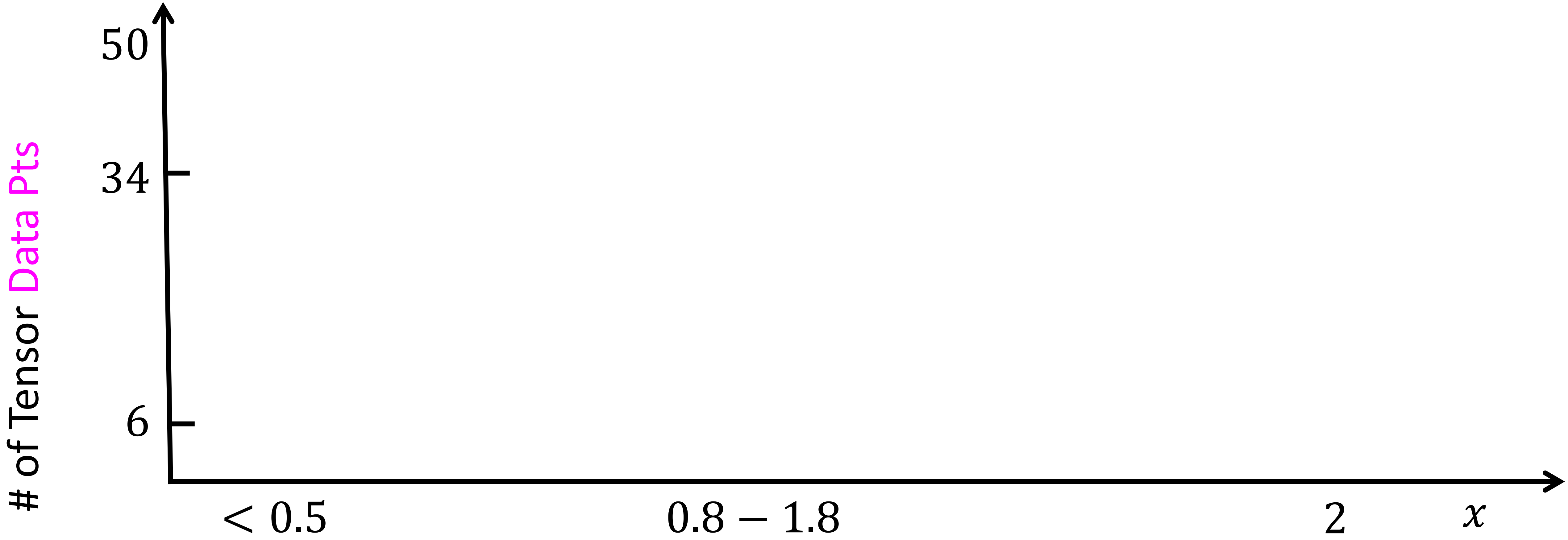

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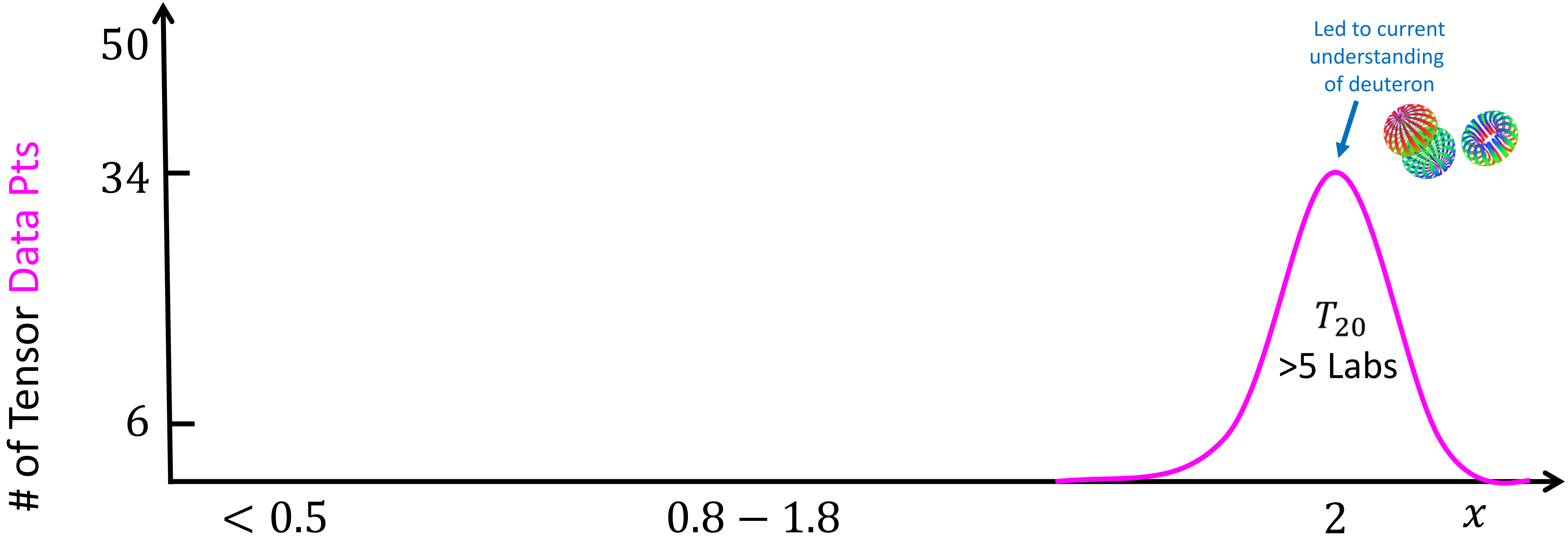
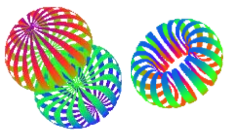
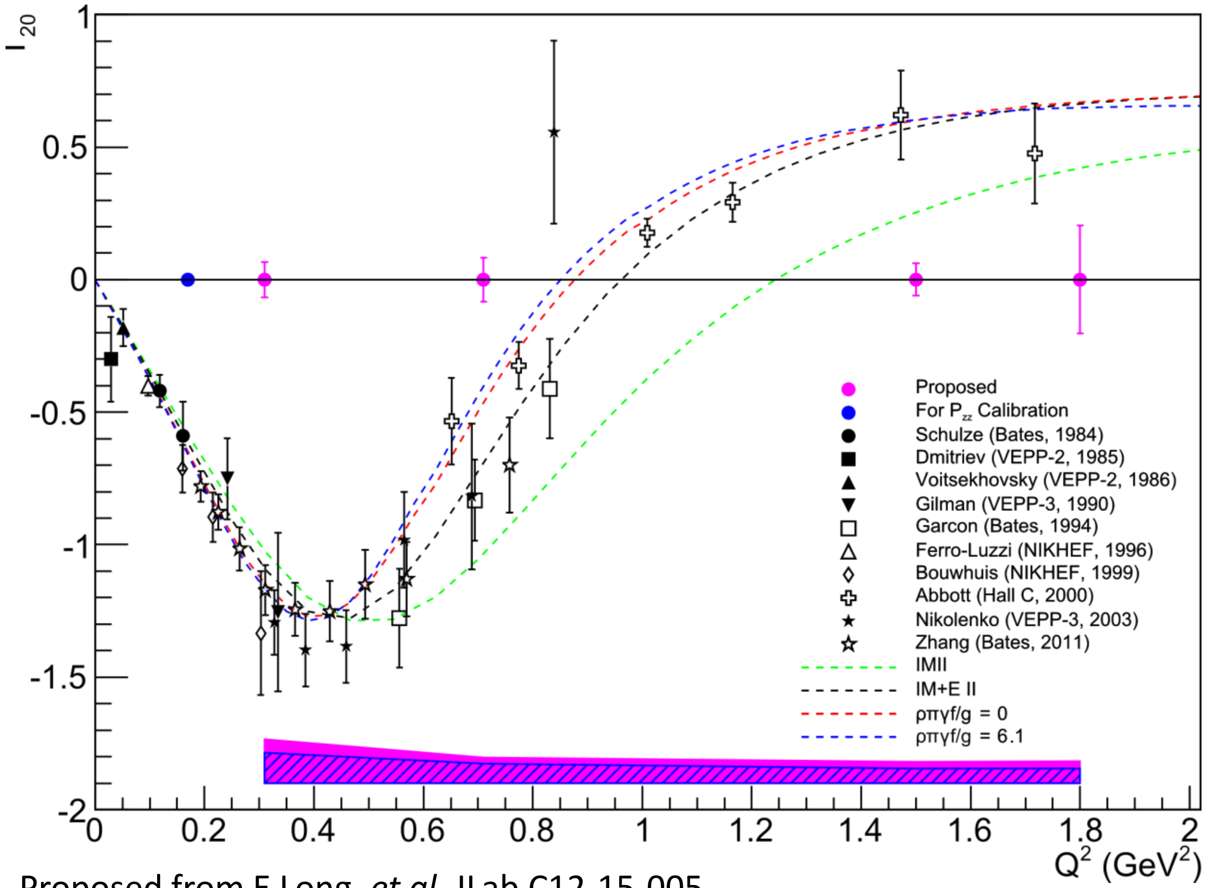


Elastic T_{20}



T_{20}, along with unpol. A & B form factors, gave rise to current deuteron understanding

$T_{20} = \frac{A_{zz}}{d_{20}\sqrt{2}}$ on elastic peak $\quad d_{20} = \frac{3\cos^2\theta^* - 1}{2}$



Proposed from E Long, *et al*, JLab C12-15-005

World Data from R Holt, R Gilman, Rept.Prog.Phys. **75** 086301 (2012)

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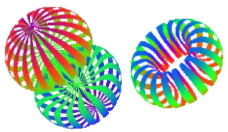

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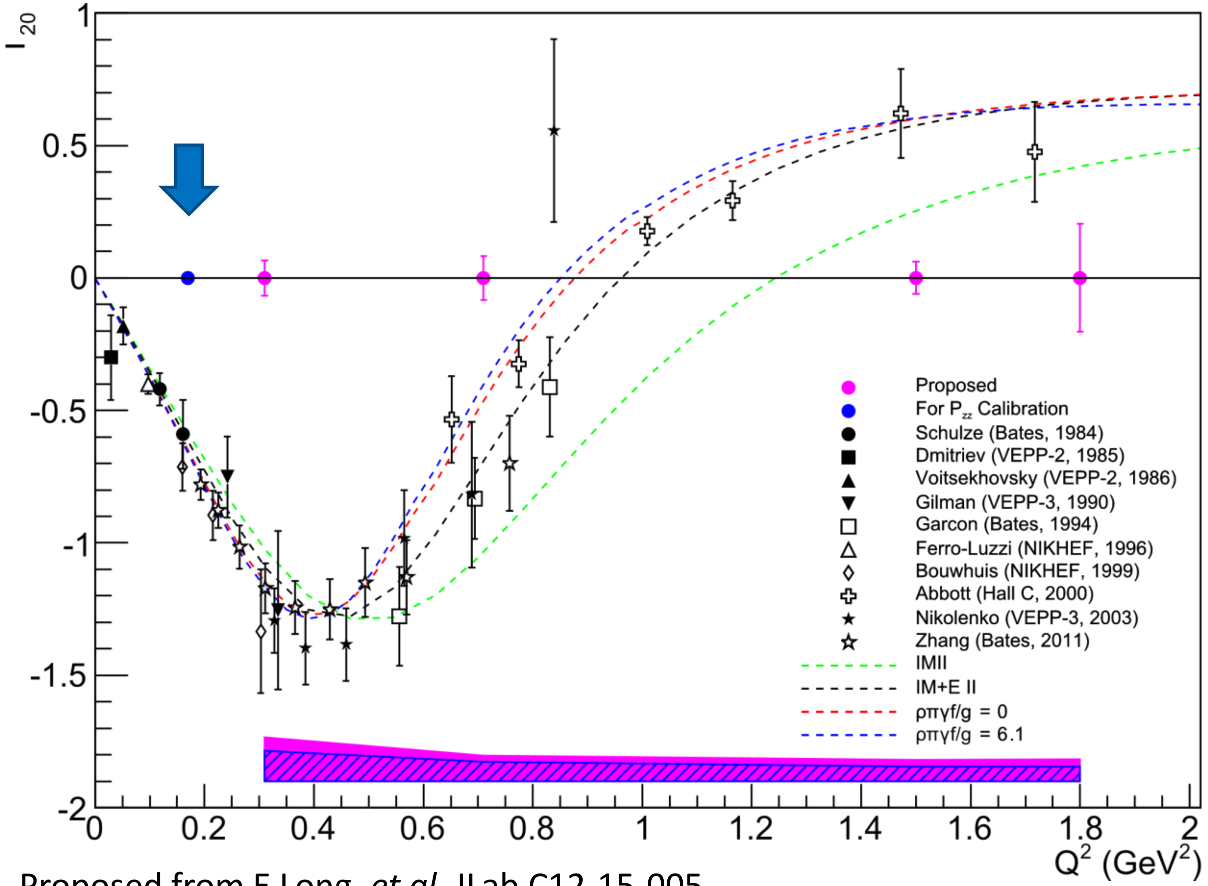
- Completely independent P_{zz} measurement from NMR line-shape P_{zz}



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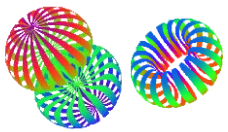

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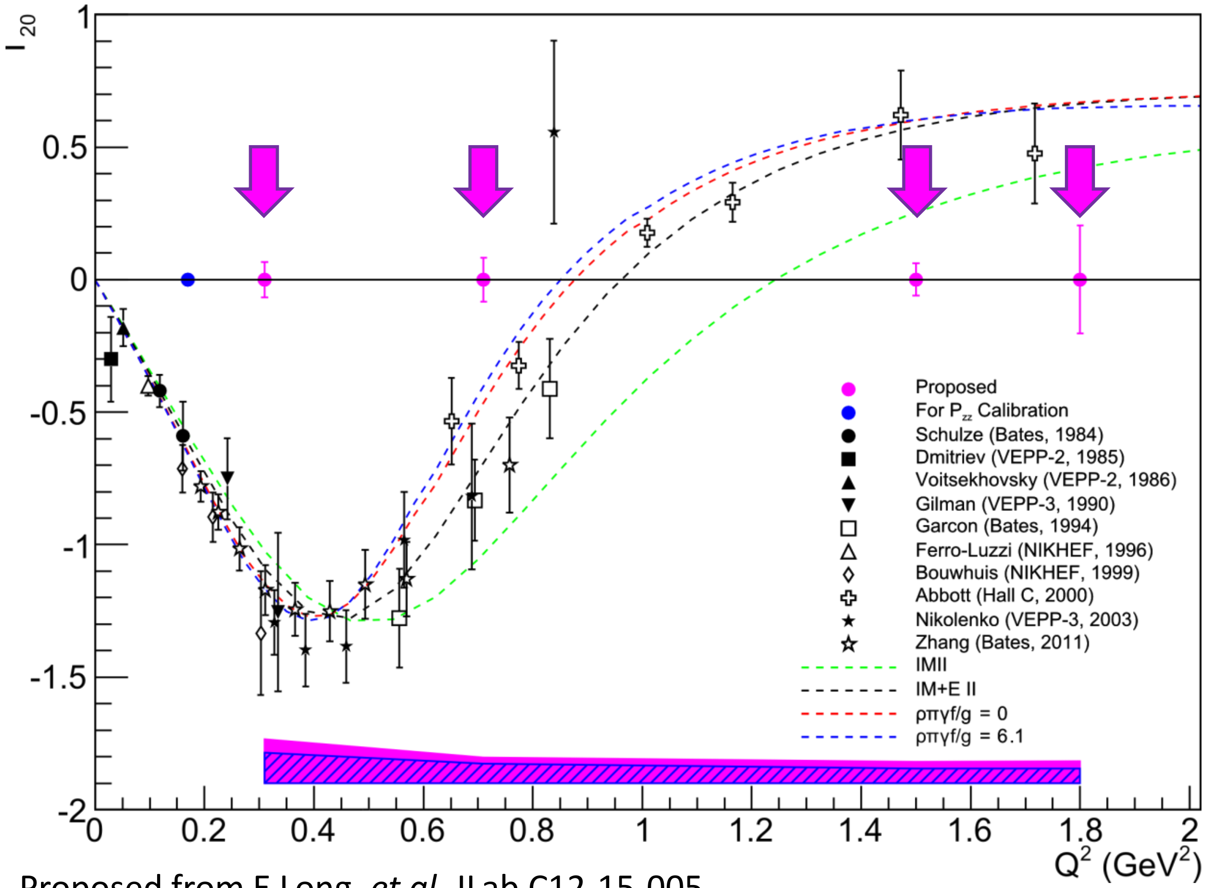
JLab E12-15-005 will measure T_{20} over the largest & highest Q^2 range

- Important cross-check of Hall C high Q^2 data



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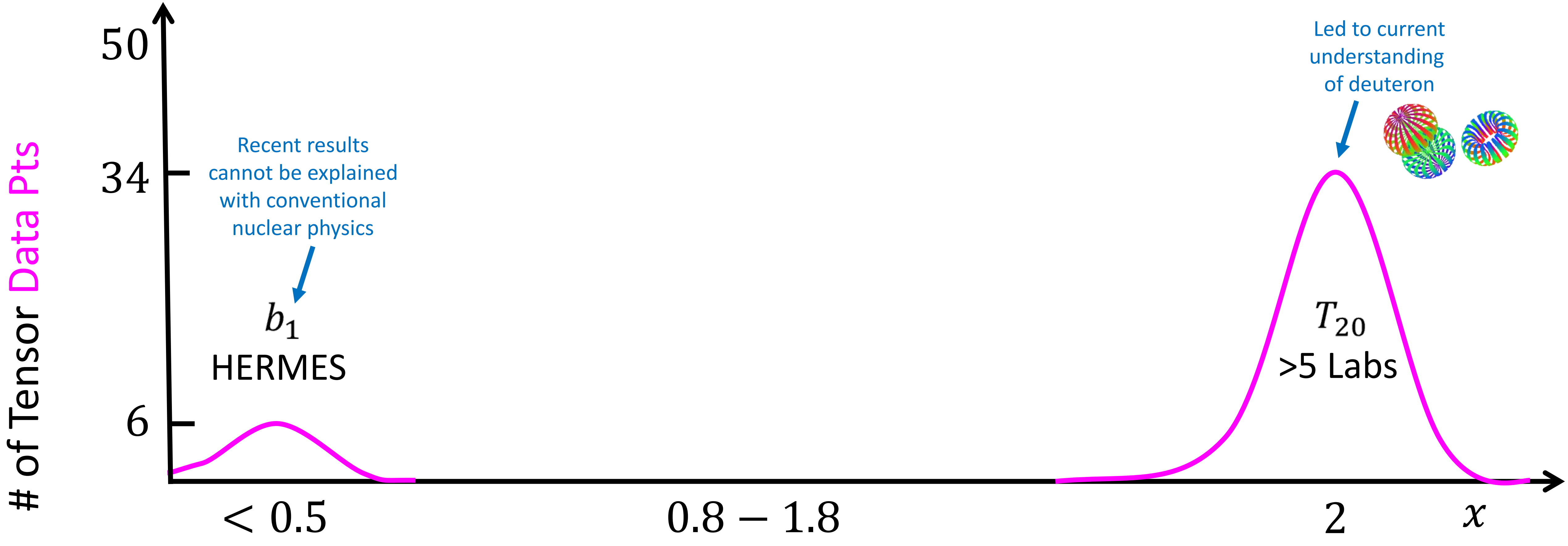
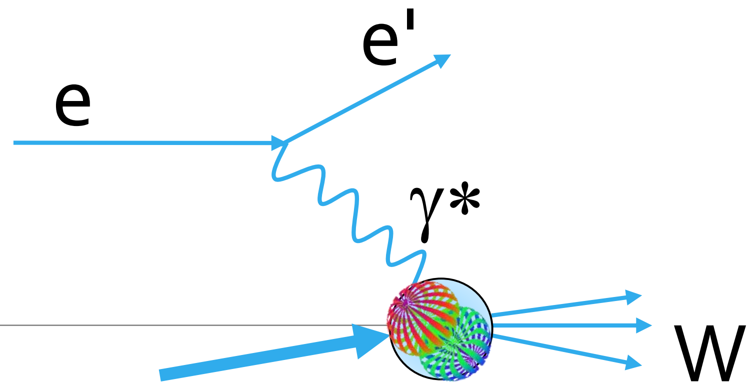


Structure Functions



Scattering on:

- Unpolarized Targets $W_{\mu\nu} = -\alpha F_1 + \beta F_2$

Existence of quarks & quark spin!

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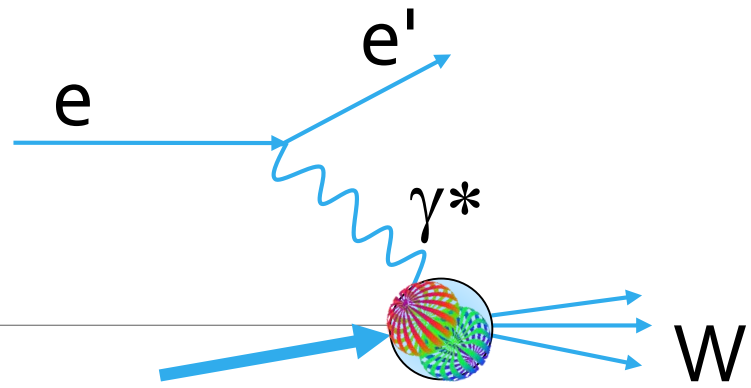

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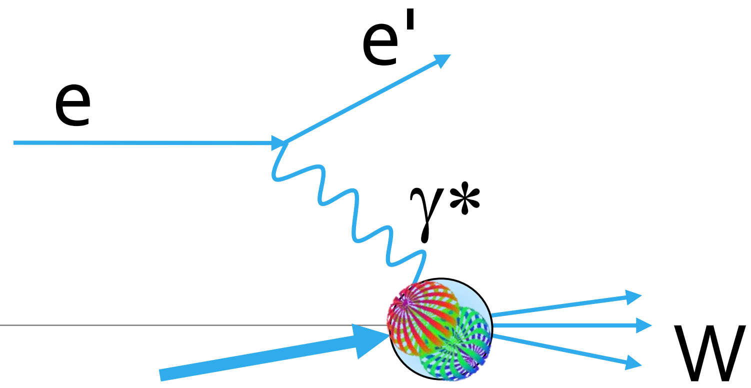

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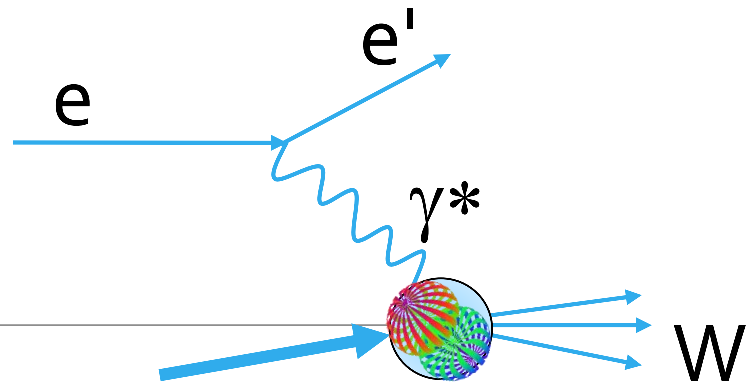

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Hidden color? Quark OAM? Sea polarization? Solving the Spin Crisis?

b_1 probes nuclear effects at quark resolution!

$$b_1(x) = \frac{q^0(x) - q^{\pm 1}(x)}{2}$$

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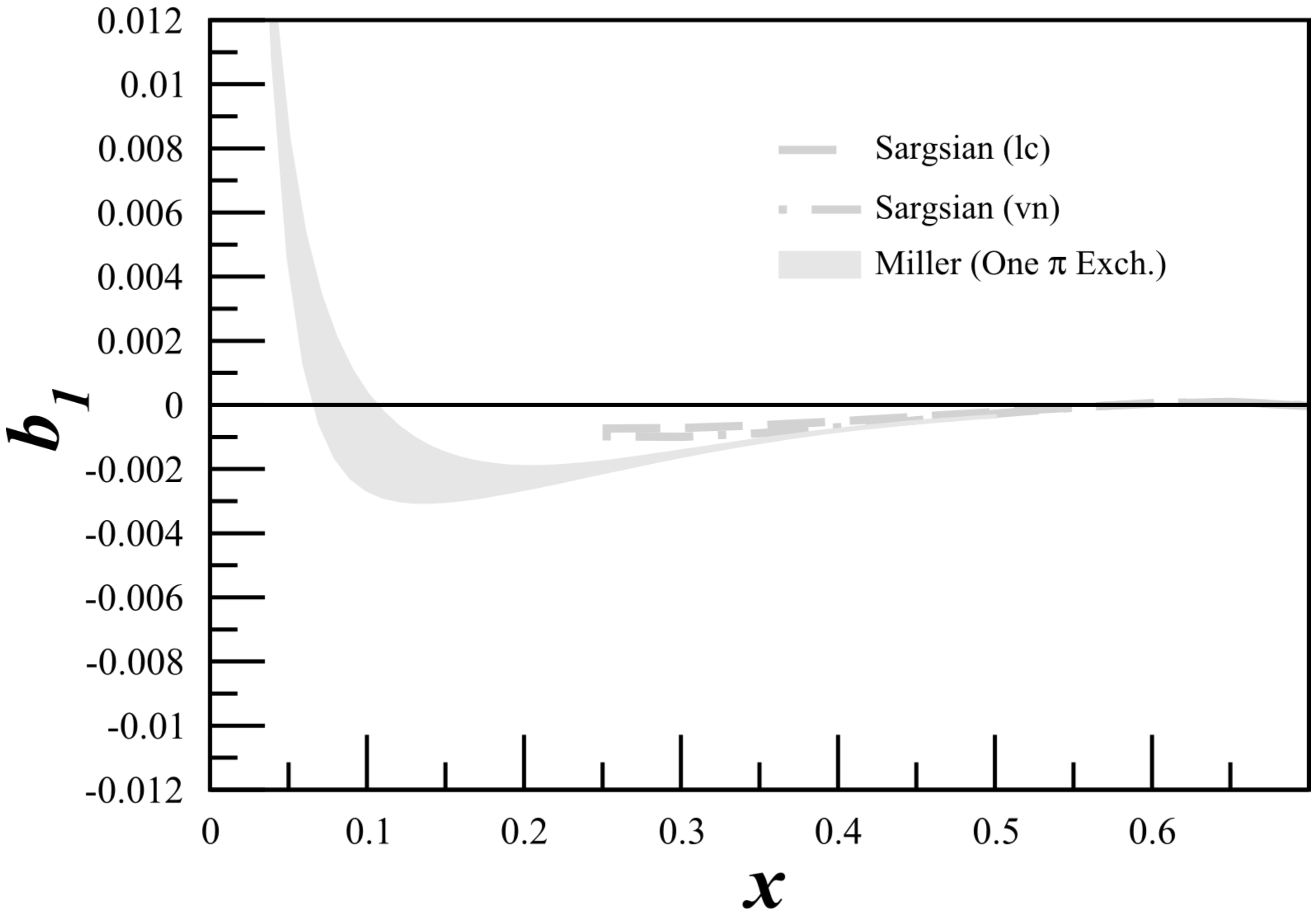
- All conventional **models predict small or vanishing values of b_1**



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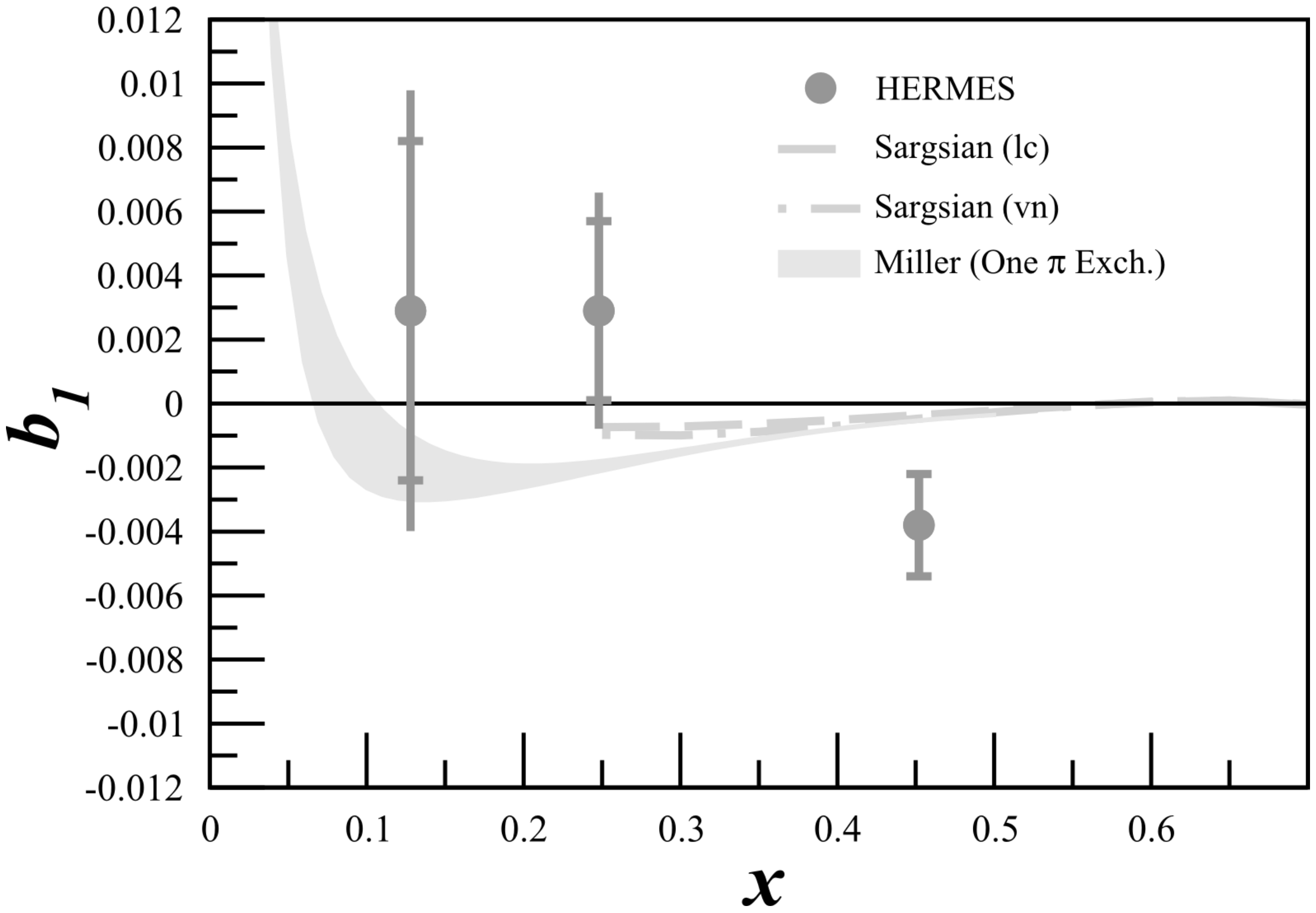

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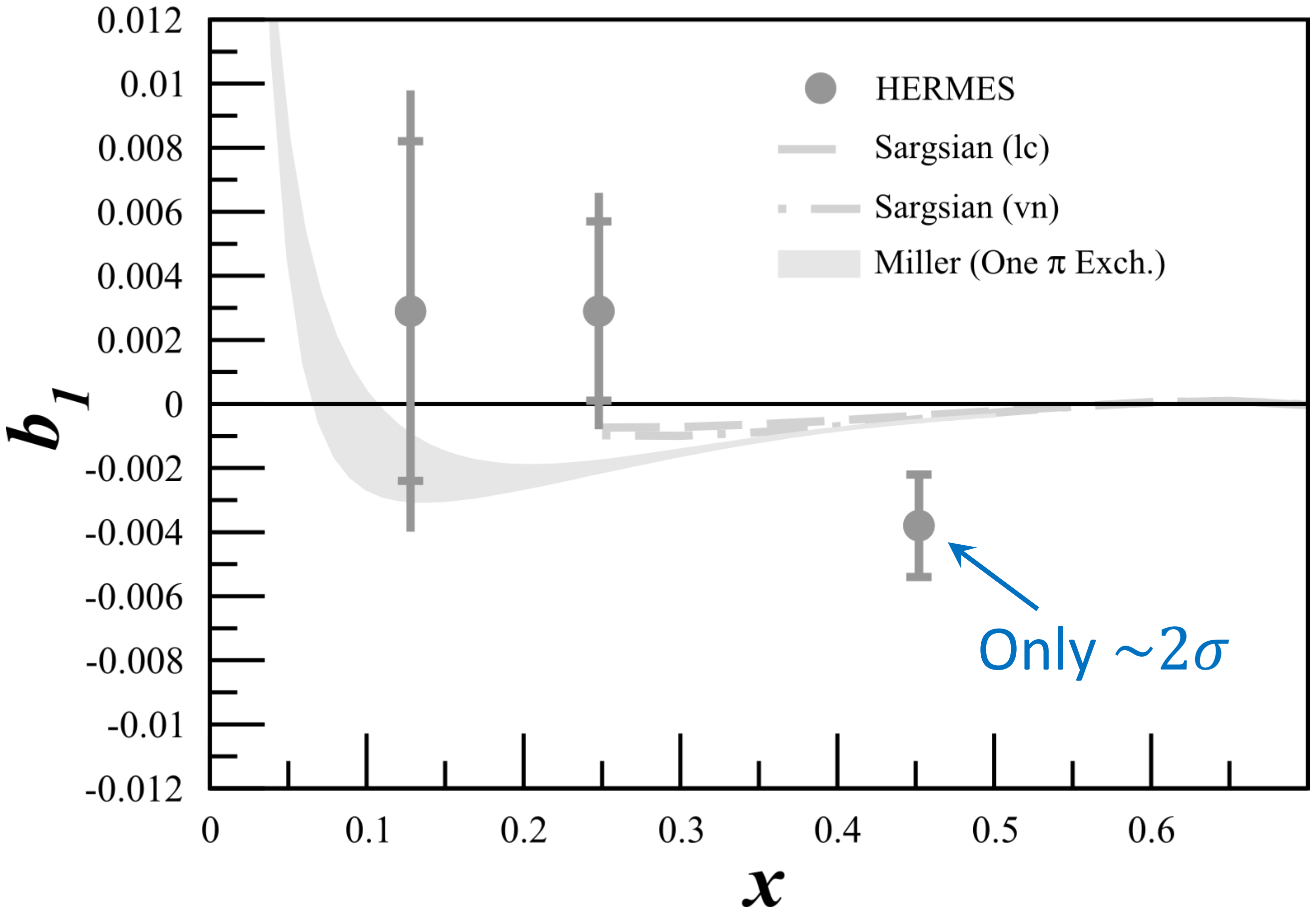

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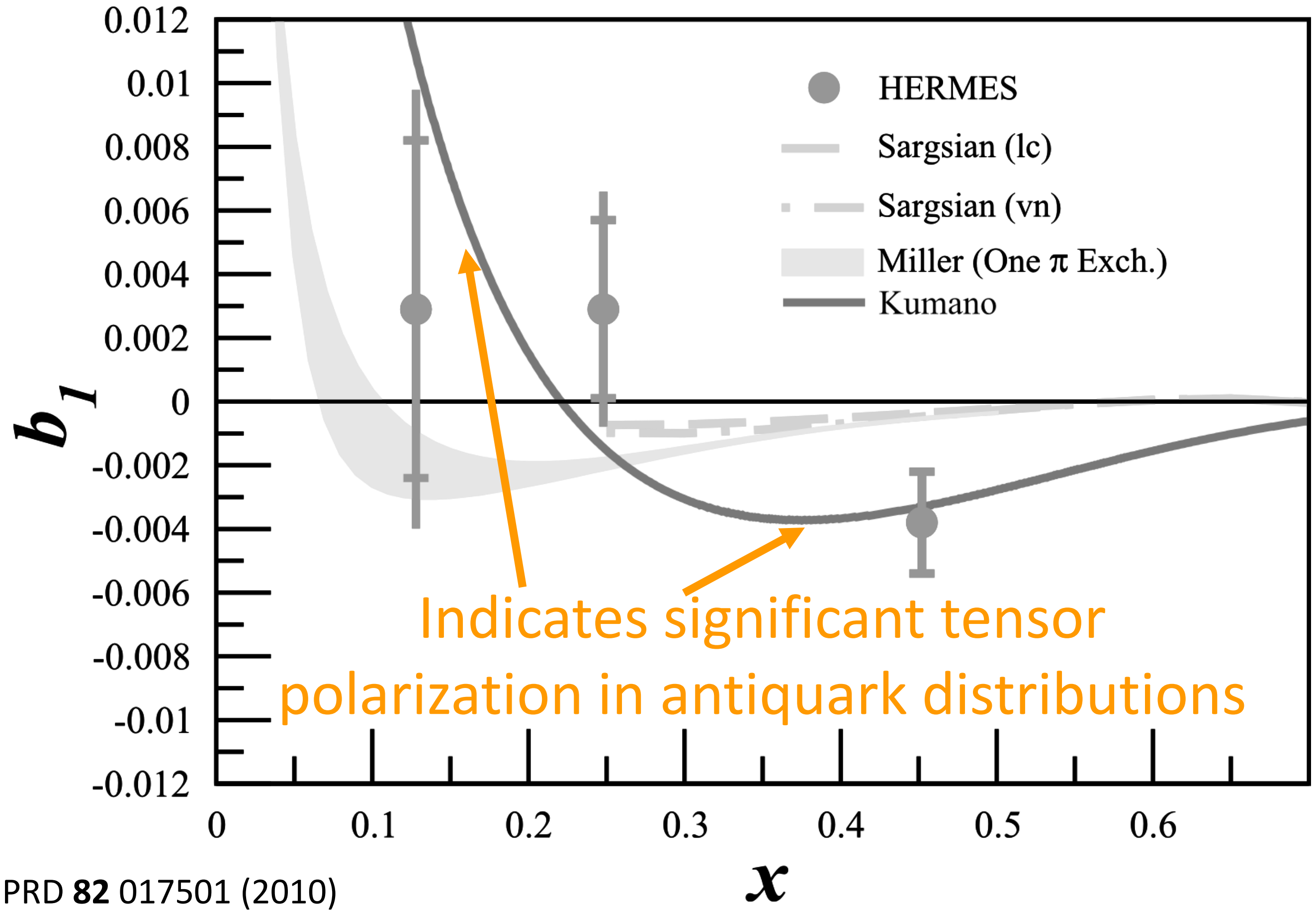

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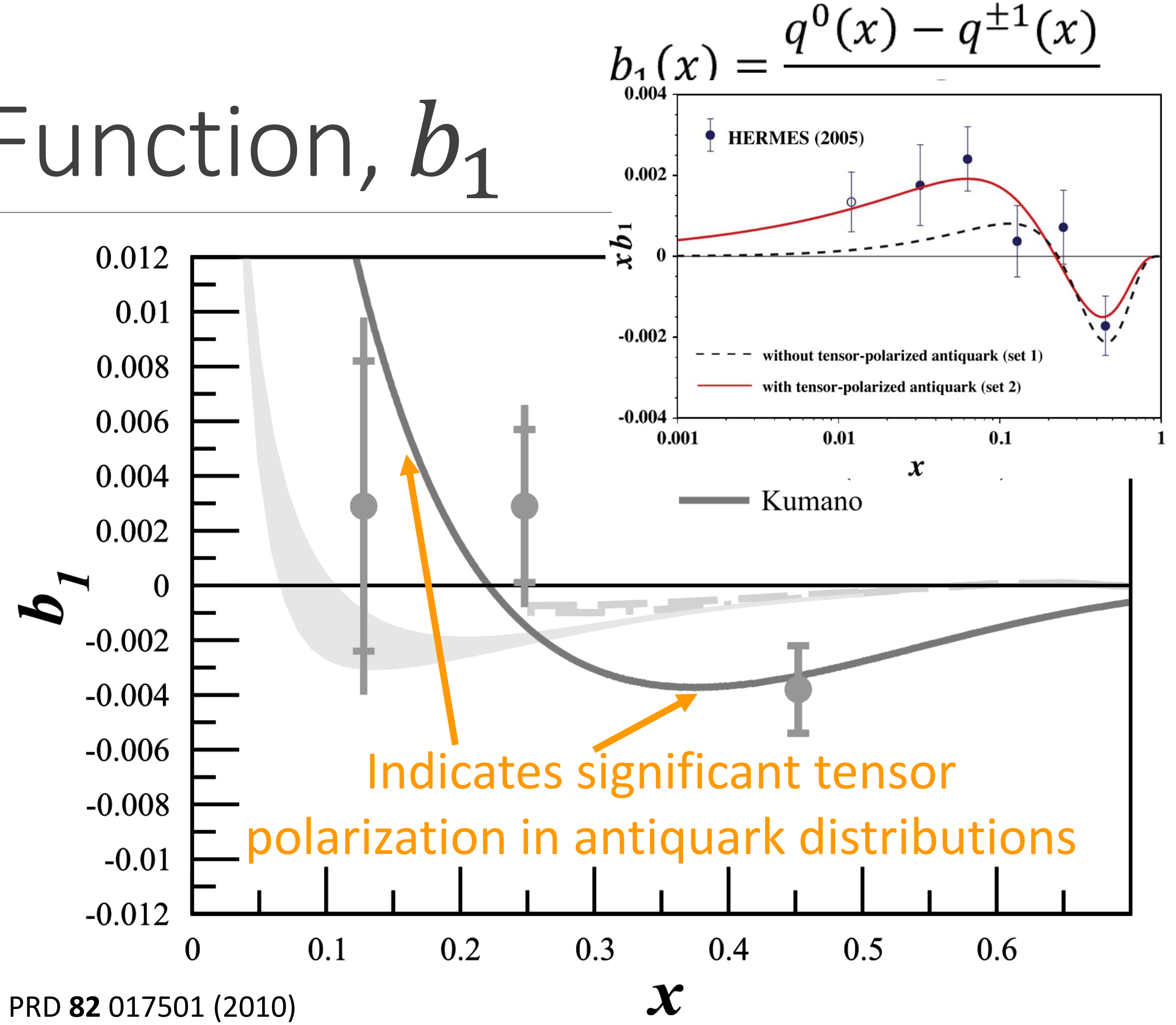

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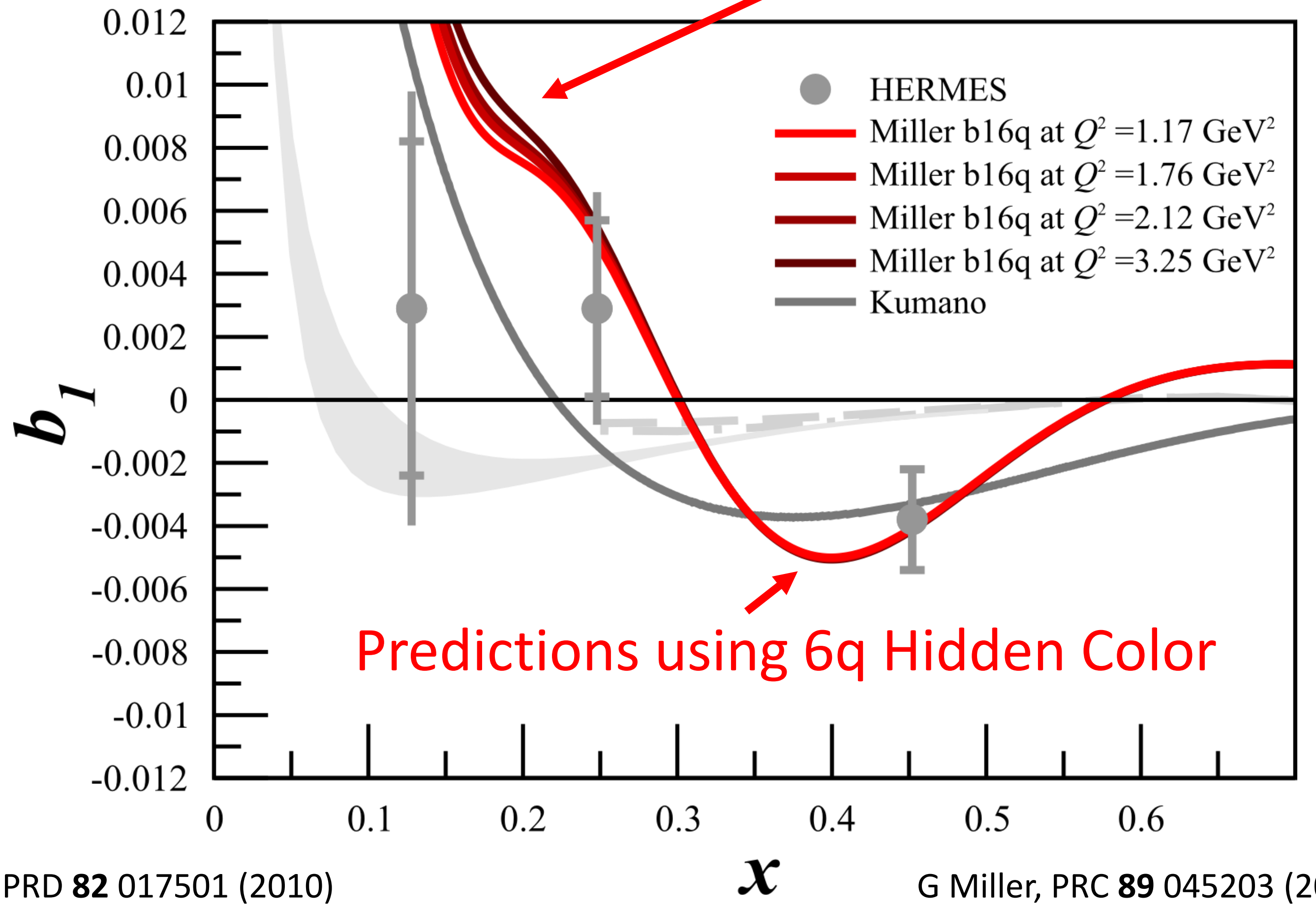

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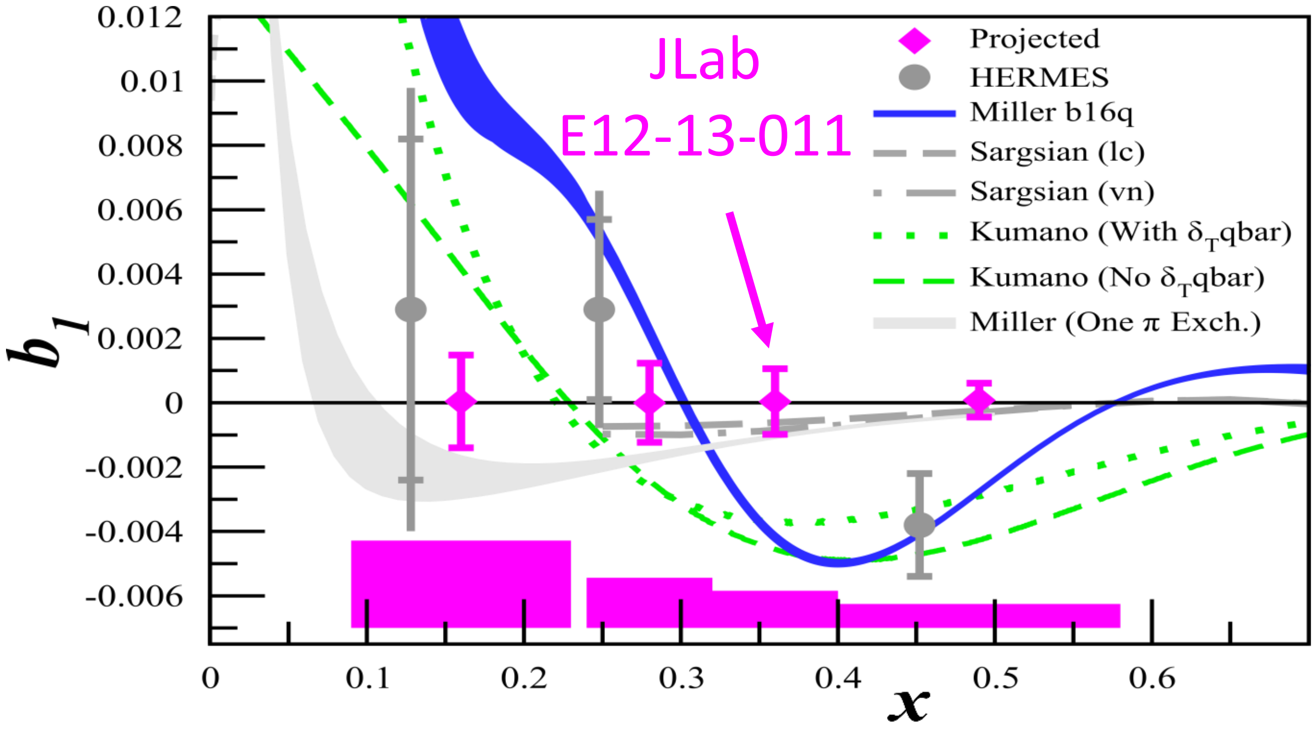

\+ Insight in Close-Kumano Sum Rule & Quark Orbital Angular Momentum

FE Close, S Kumano, PRD **42** 2377 (1990)

SK Taneja *et al*, PRD **86** 036008 (2012)

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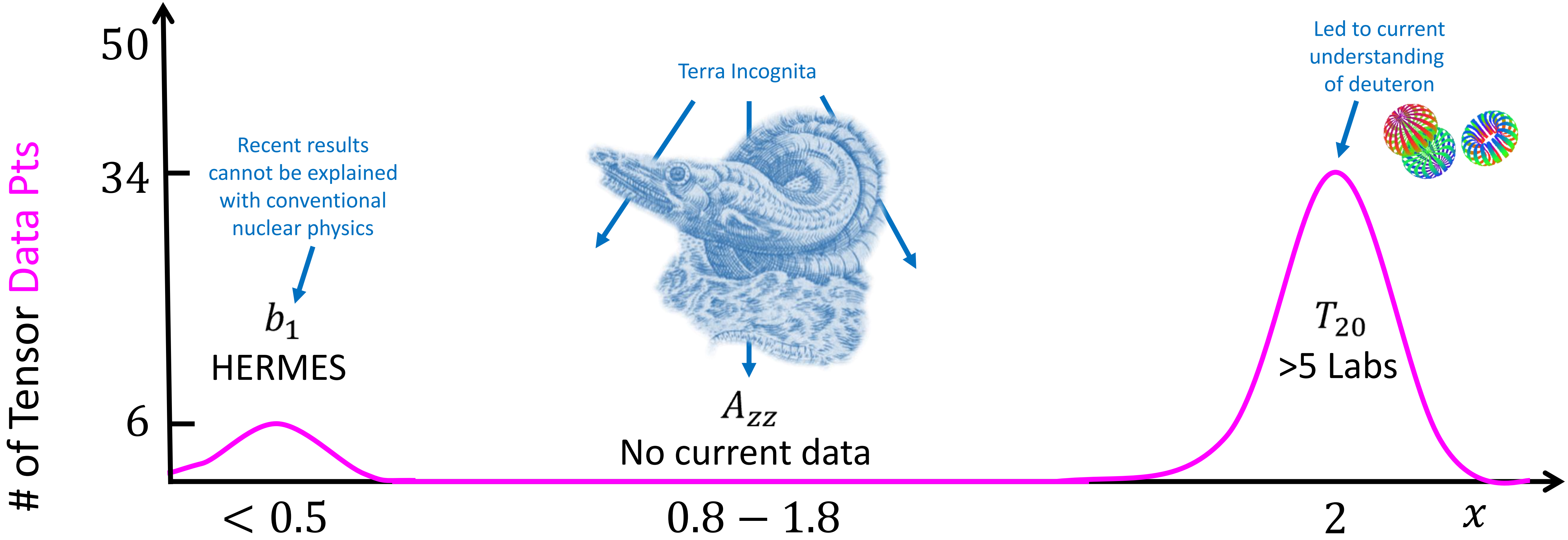

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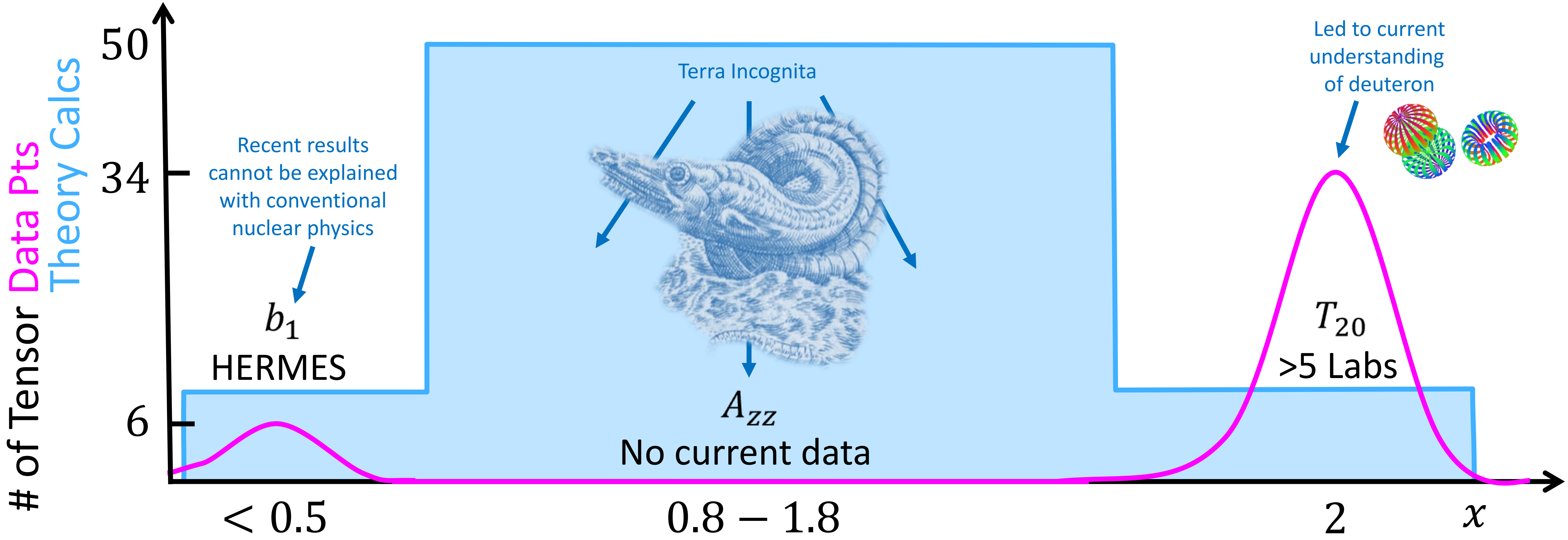
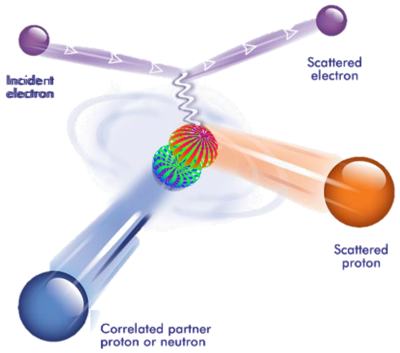


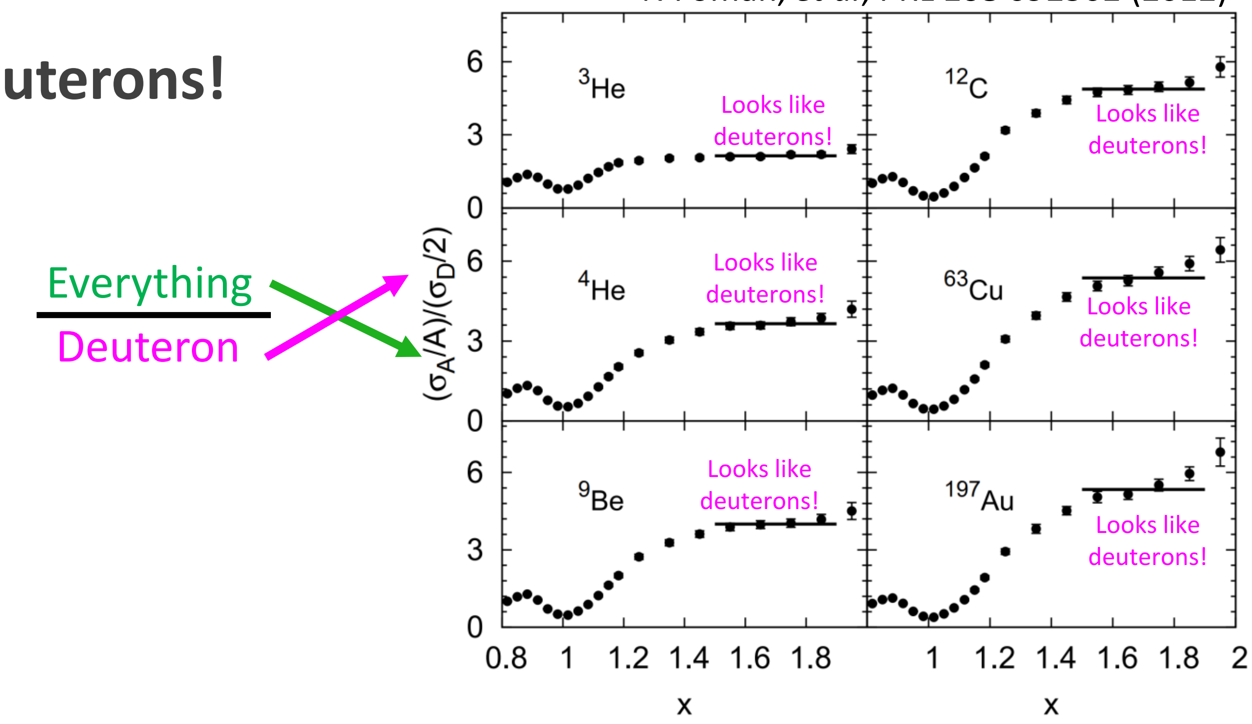
Matter at Small Distances & High Momentum



- Short-Range Correlations:

Everything looks like deuterons!

N Foman, *et al*, PRL **108** 092502 (2012)



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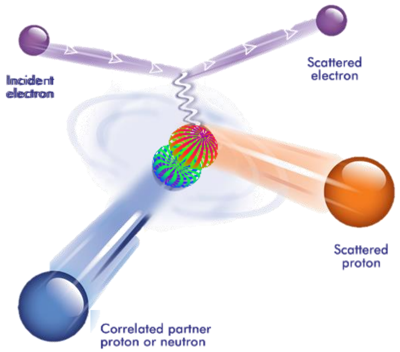

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Everything / Deuteron

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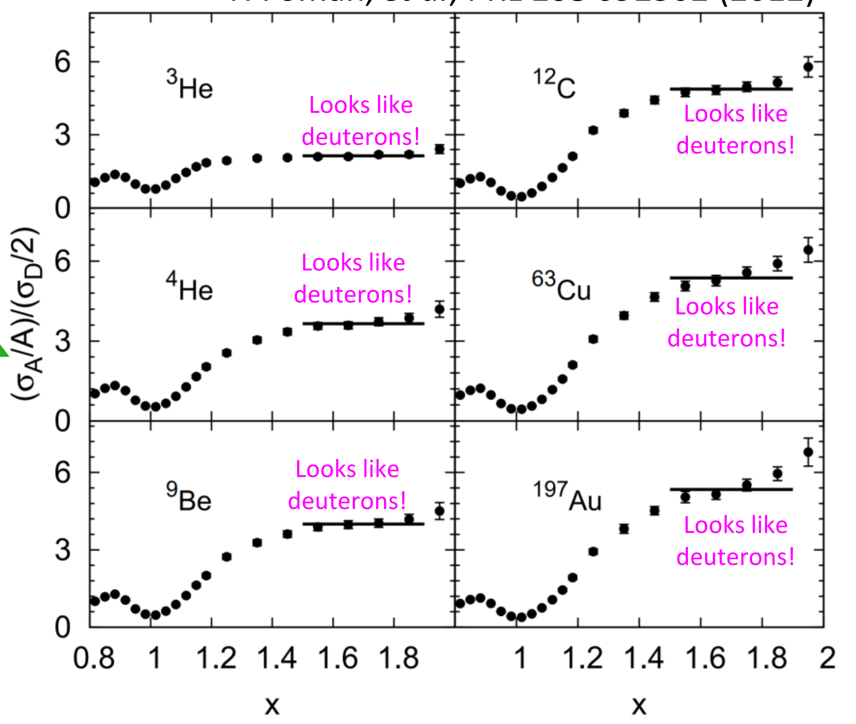
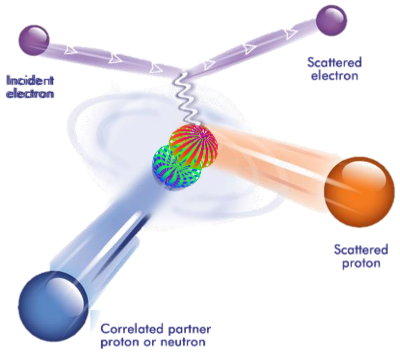


Look @ Deuteron: Simplest composite nuclear system

Matter at Small Distances & High Momentum



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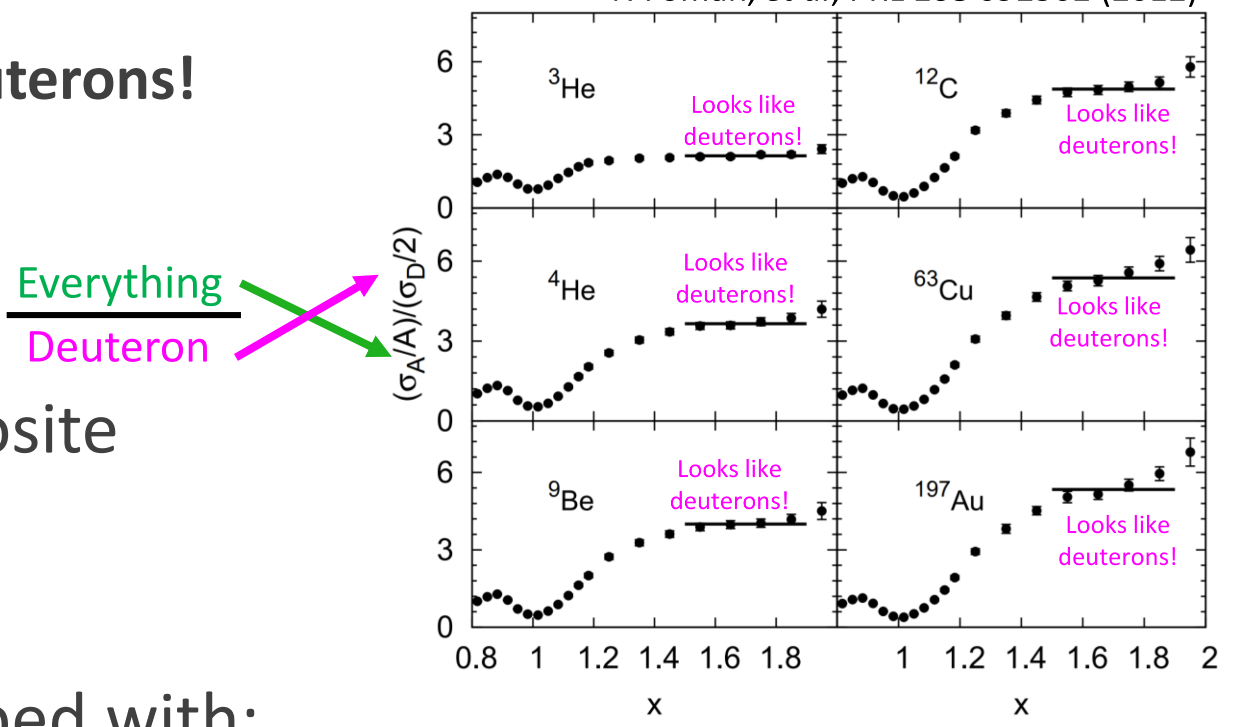

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Short-range, high *p* structure probed with:

- $x > 1$ kinematics
- Enhancing tensor polarization

We combine both techniques

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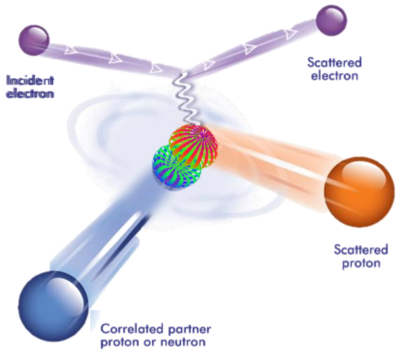

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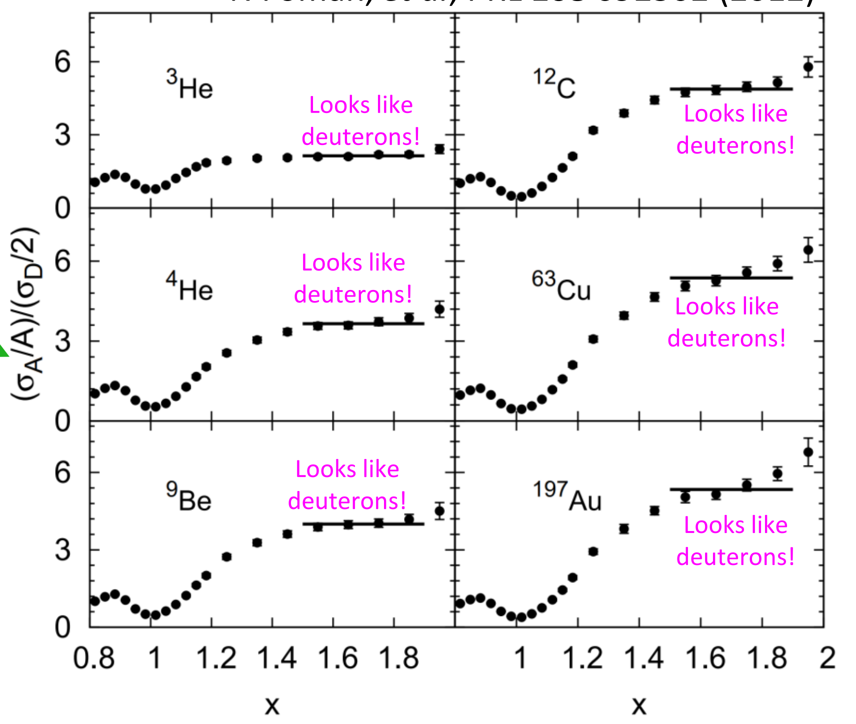
Probe the tensor force with tensor polarization!

N Foman, *et al*, PRL **108** 092502 (2012)



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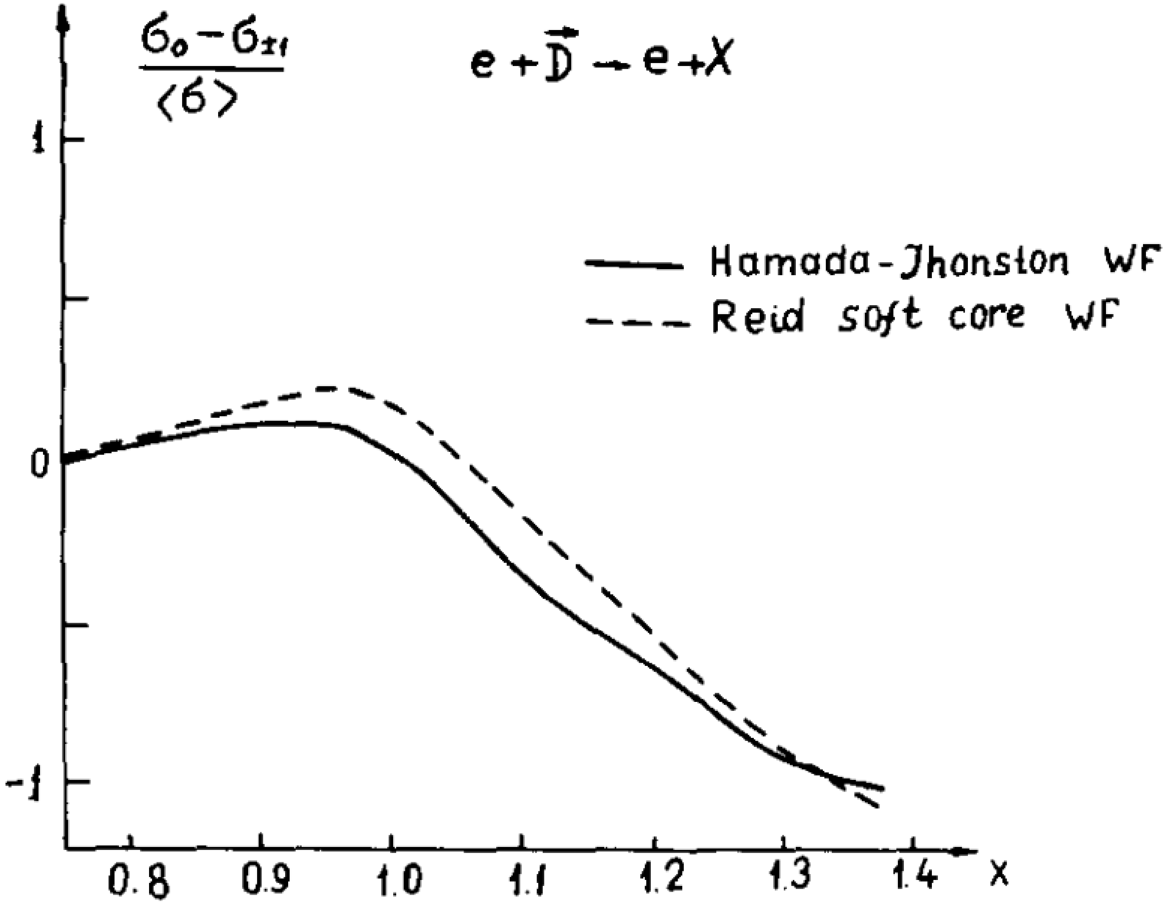
"There is a strong need for models of the deuteron wave function that are both **realistic** and relativistic." - J. Terry, G. Miller, arXiv:1603.07032 (2016)

Deuteron Wavefunction

First calculated in the '70s, A_{zz} can be used in to discriminate between hard and soft wave functions

$$A_{zz} = \frac{2}{f \cdot P_{zz}}\left(\frac{\sigma_p - \sigma_u}{\sigma_u}\right)$$



LL Frankfurt, MI Strikman, Phys. Rept. **76** 215 (1981)

"There is a strong need for models of the deuteron wave function that are both **realistic** and relativistic." - J. Terry, G. Miller, arXiv:1603.07032 (2016)

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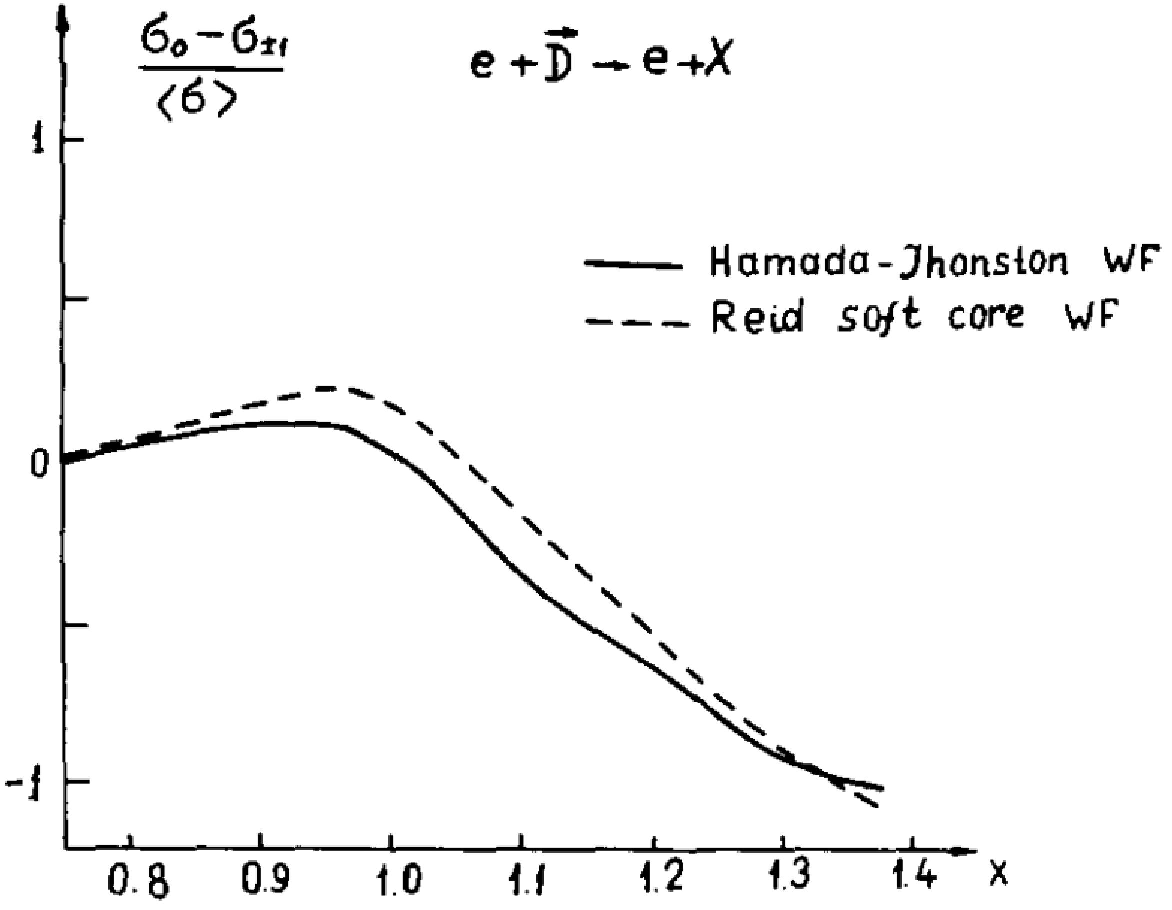

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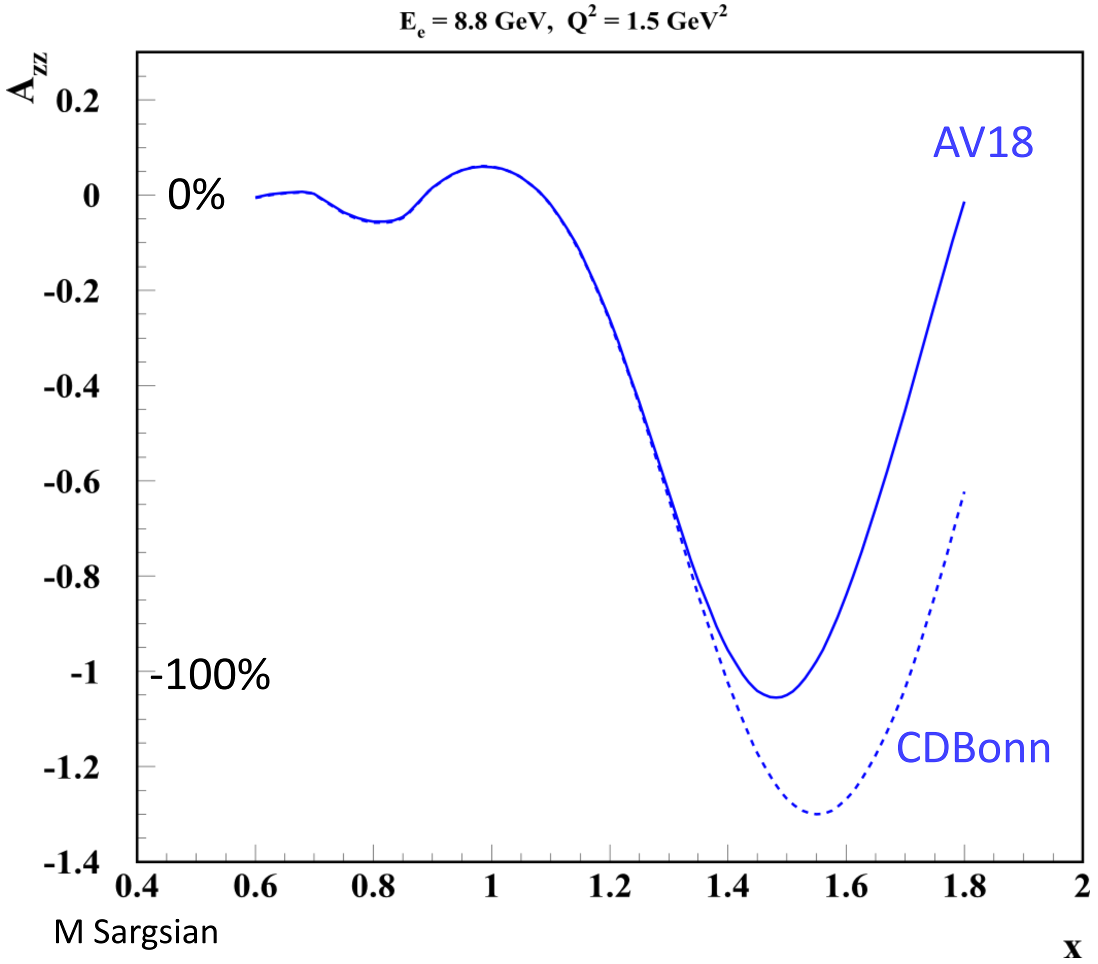

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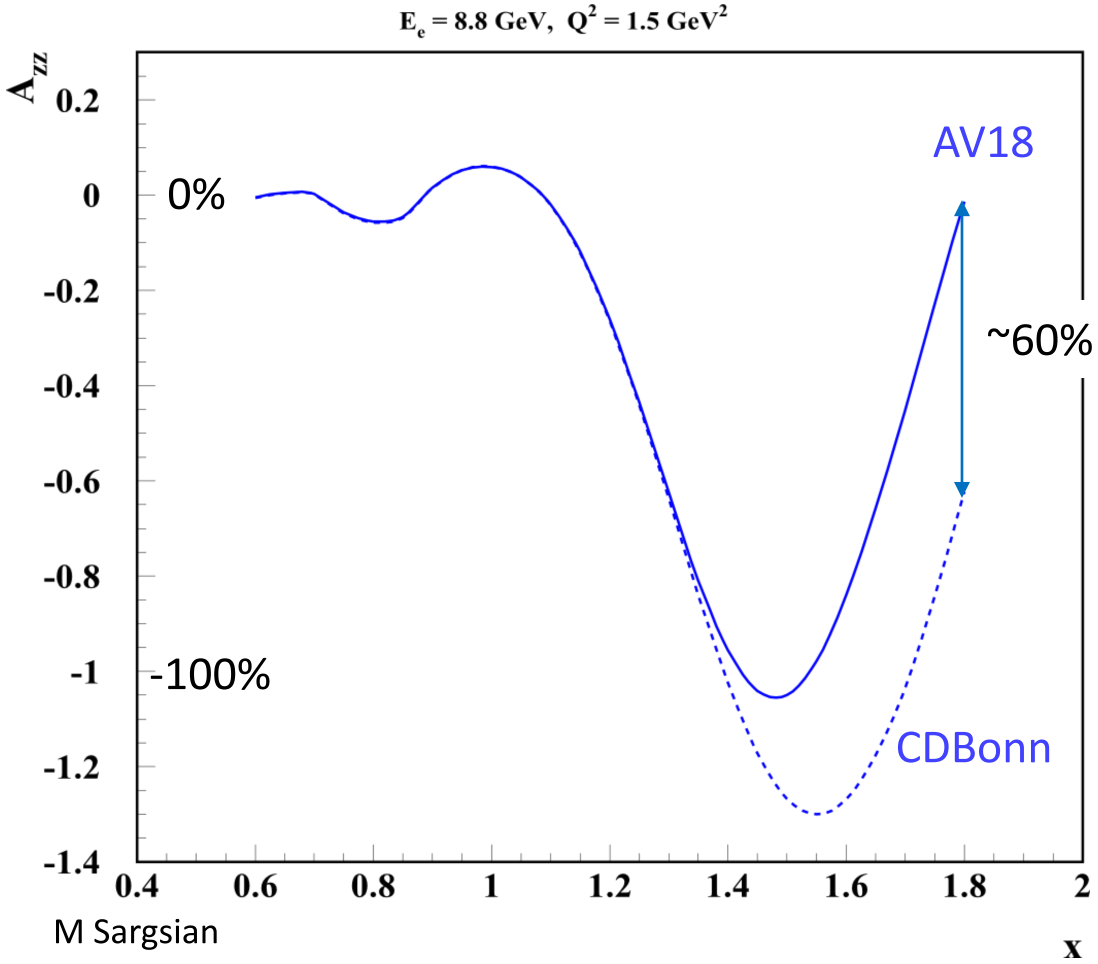

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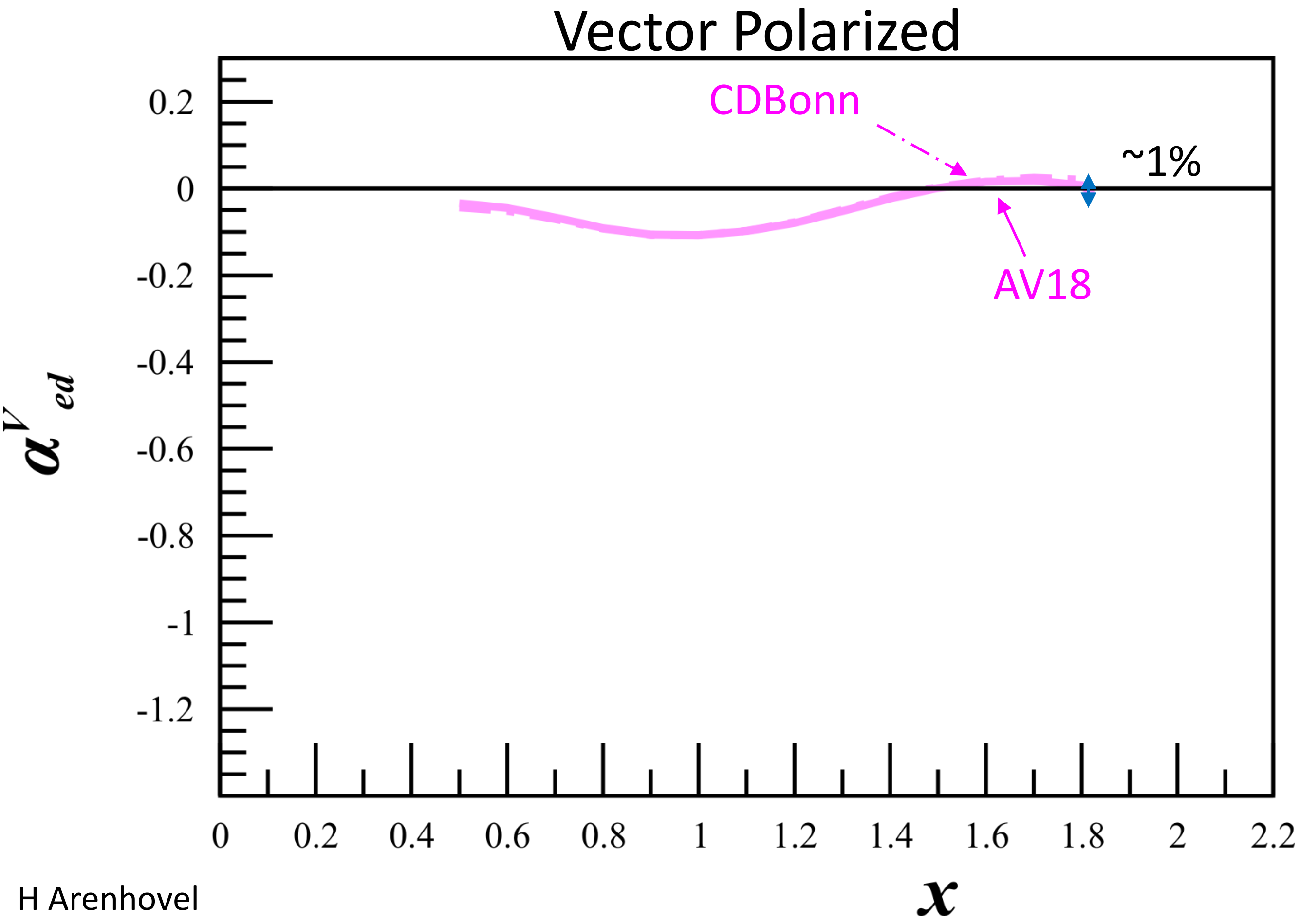

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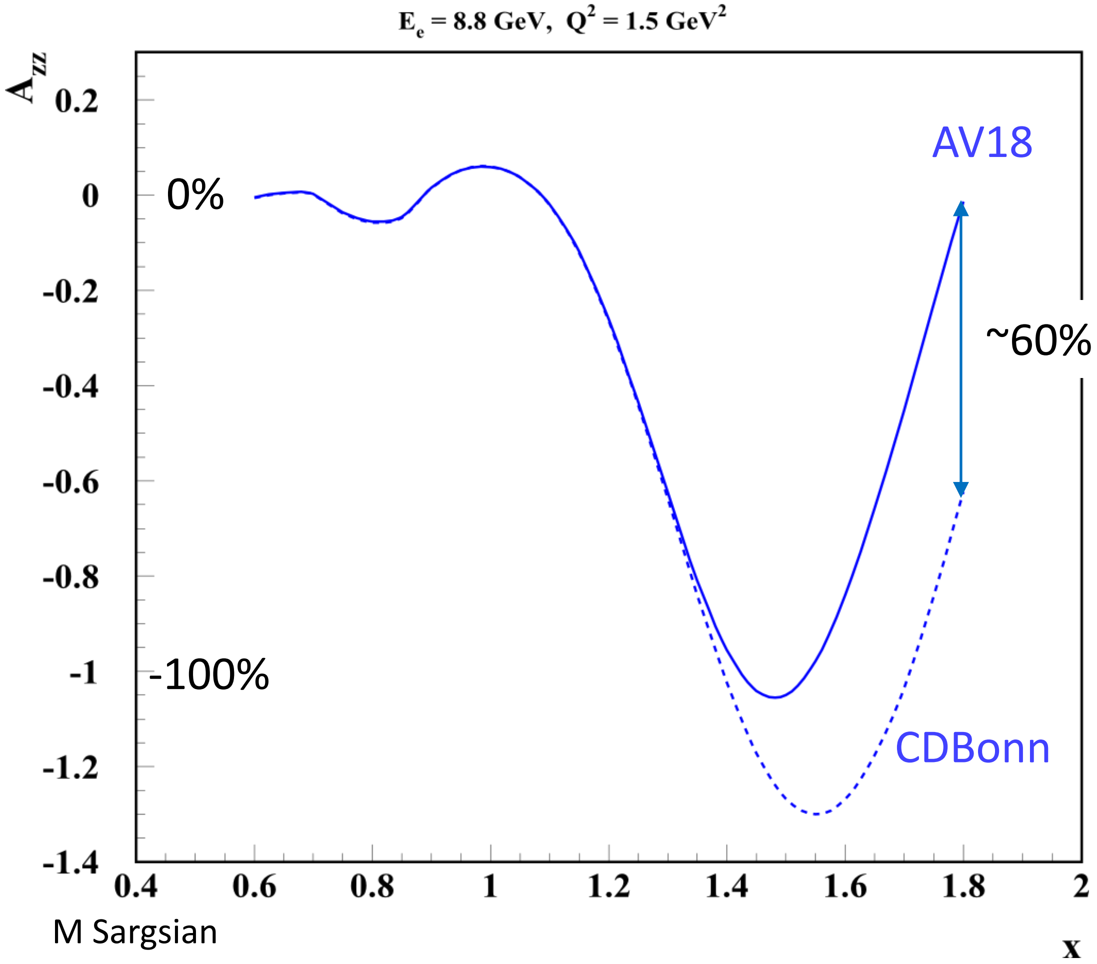

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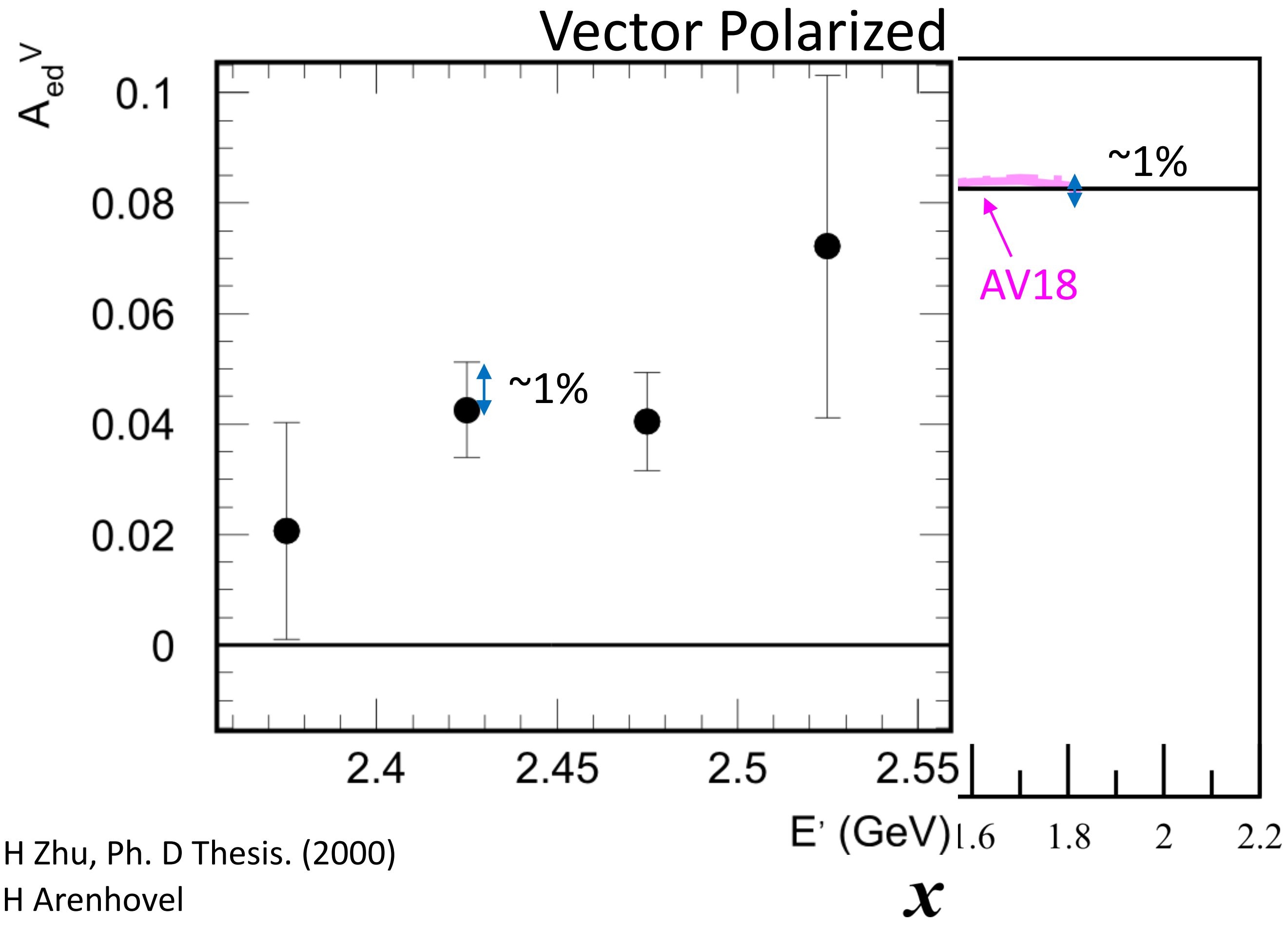

H Zhu, Ph. D Thesis. (2000)
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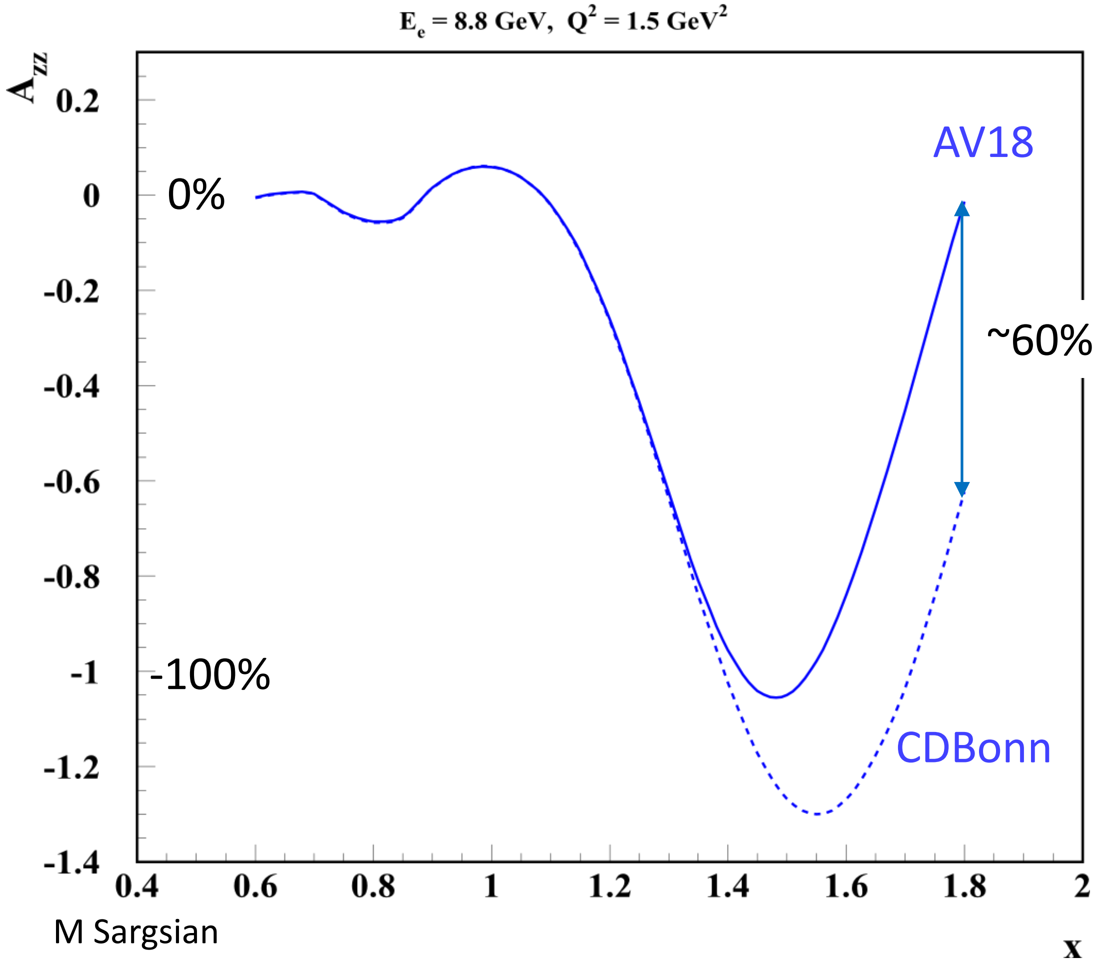

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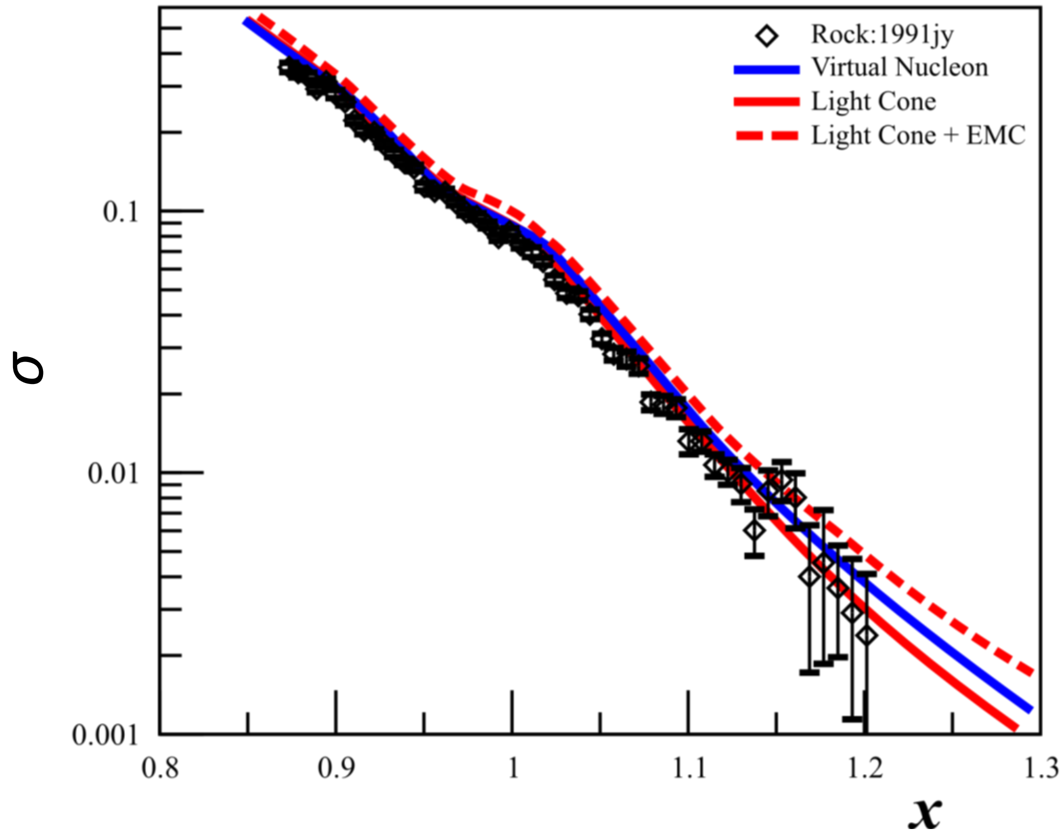
Relativistic *NN* Bound System

Unpolarized



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Currently two methods:

- Light Cone (LC)
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Large $p > 500\ \mathrm{MeV}/c$ needed to discriminate with unpolarized deuterons

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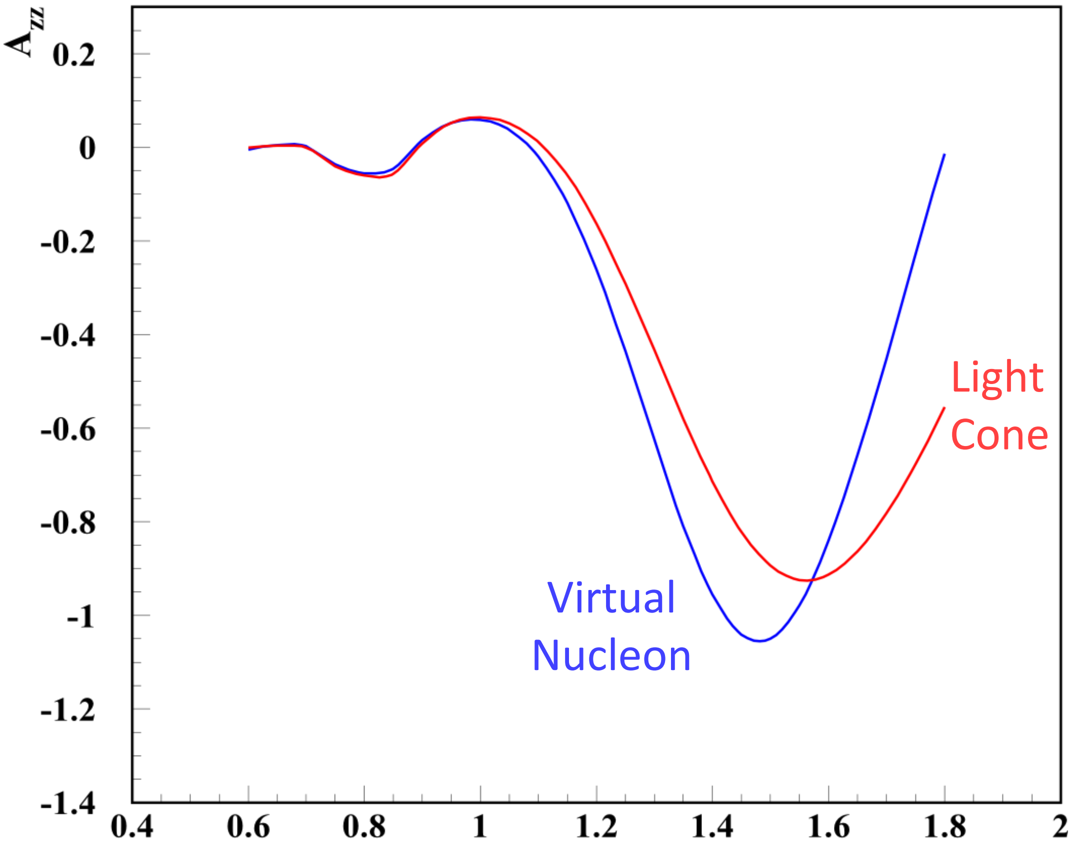

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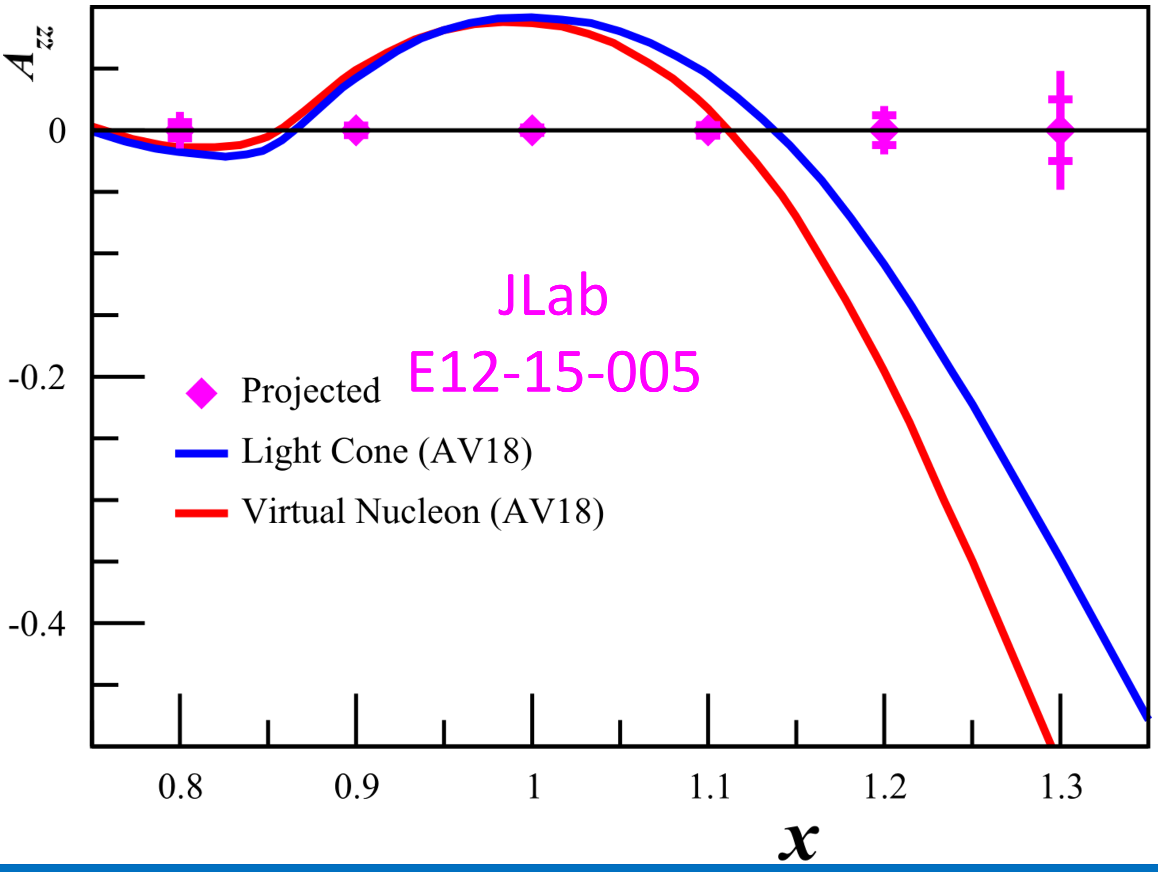

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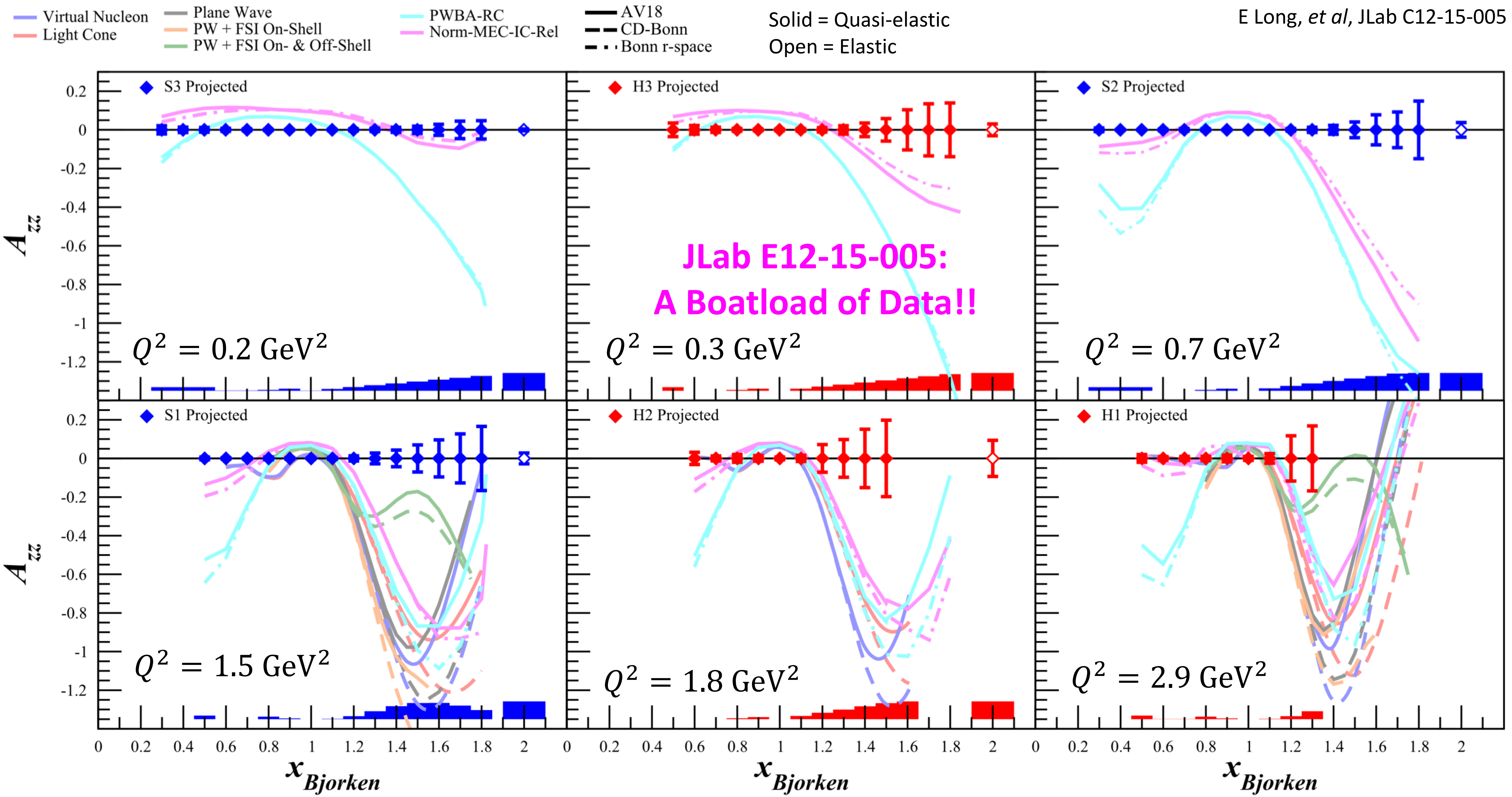

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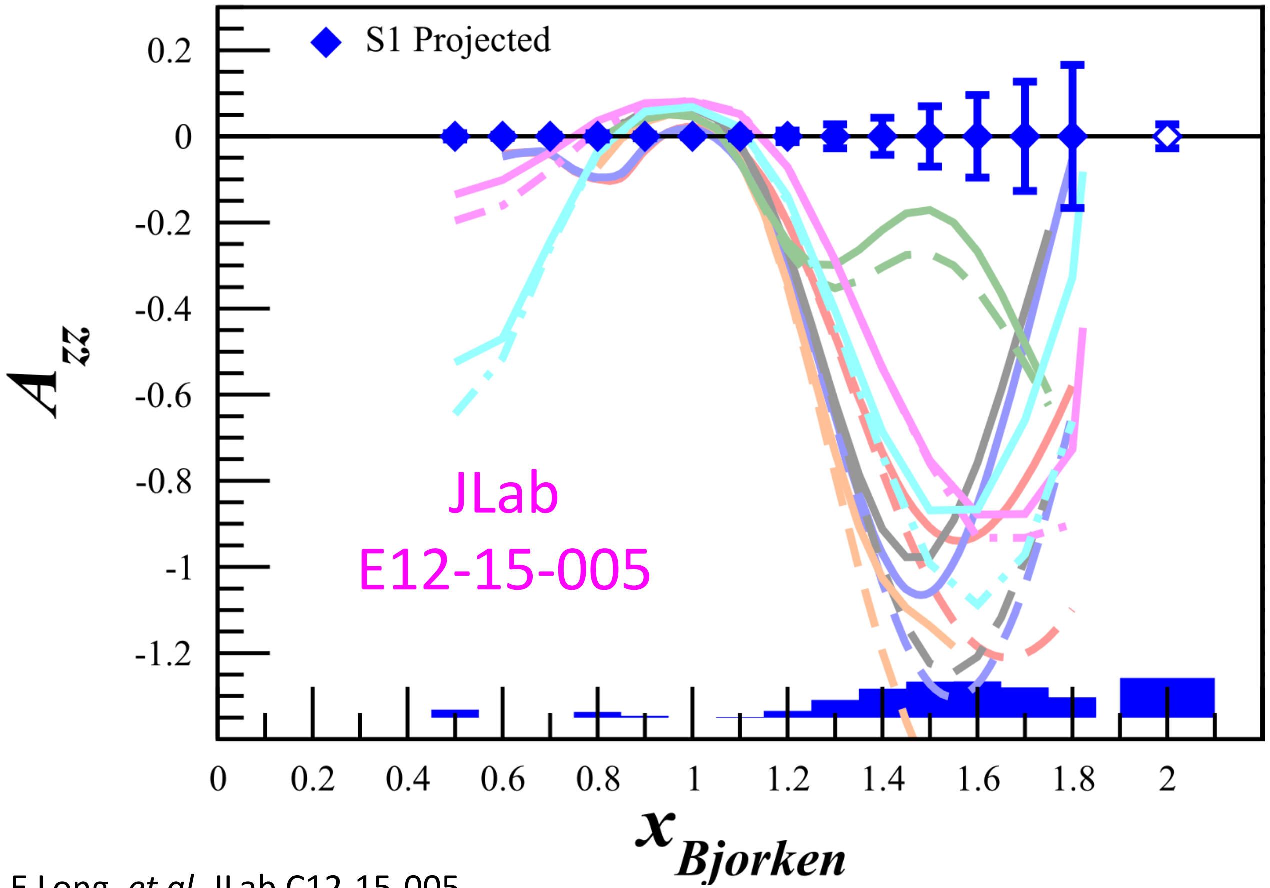

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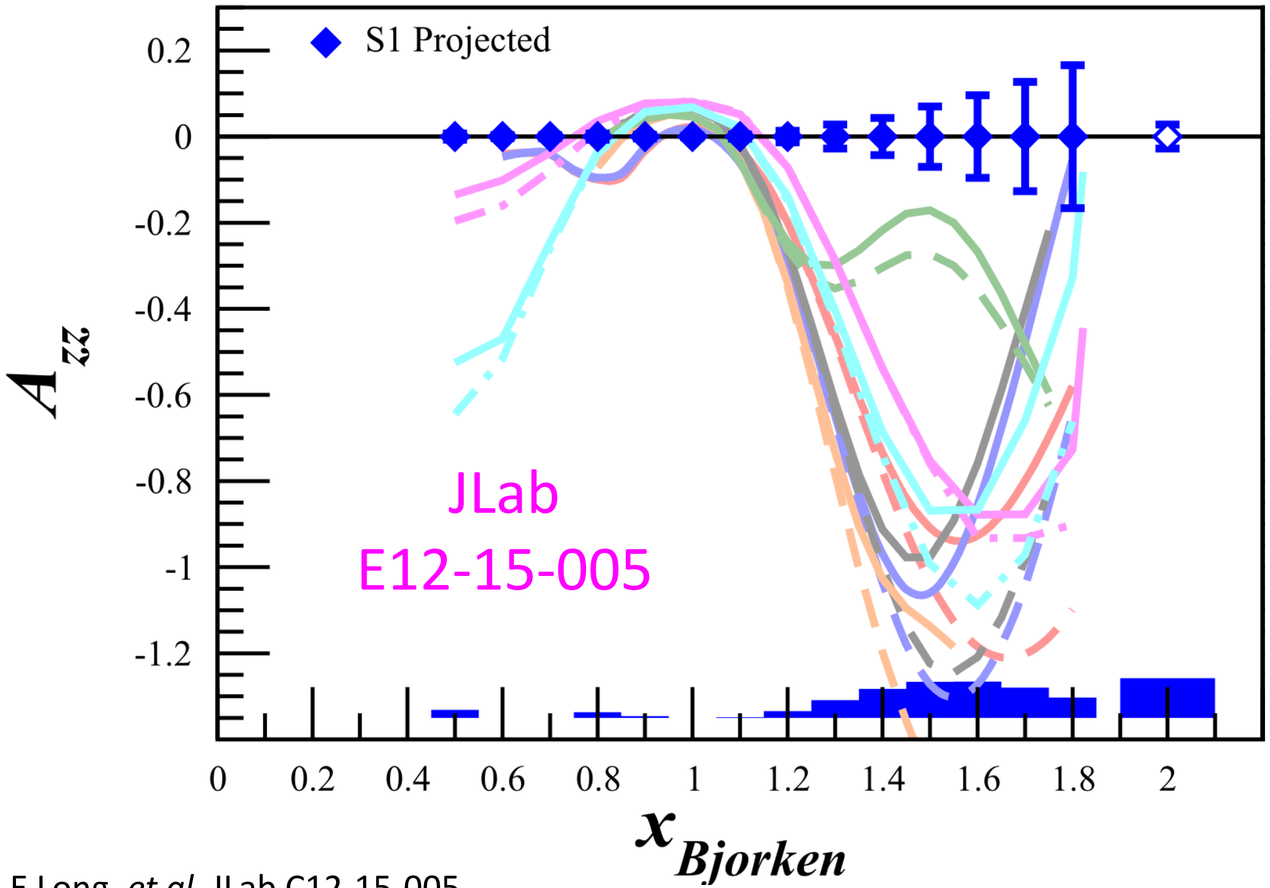

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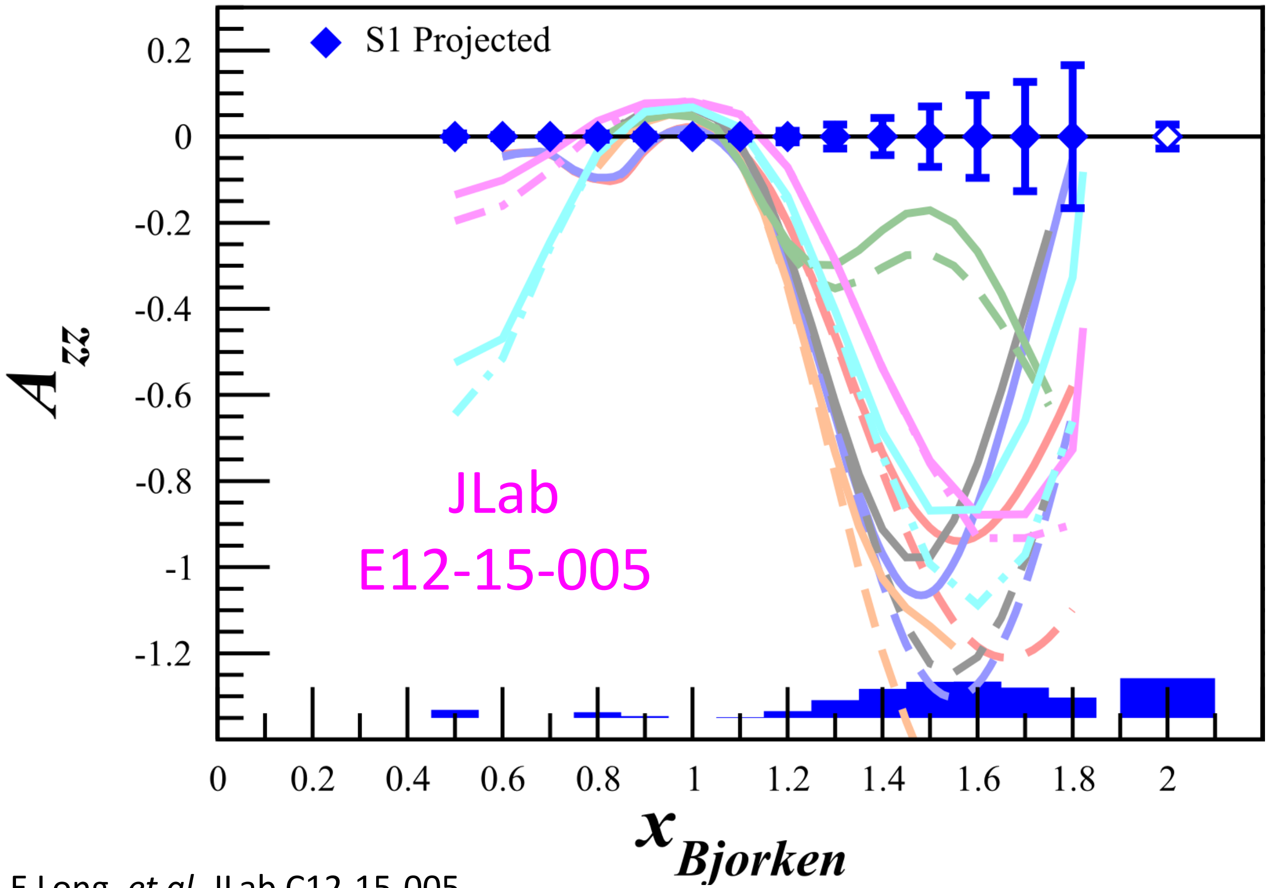

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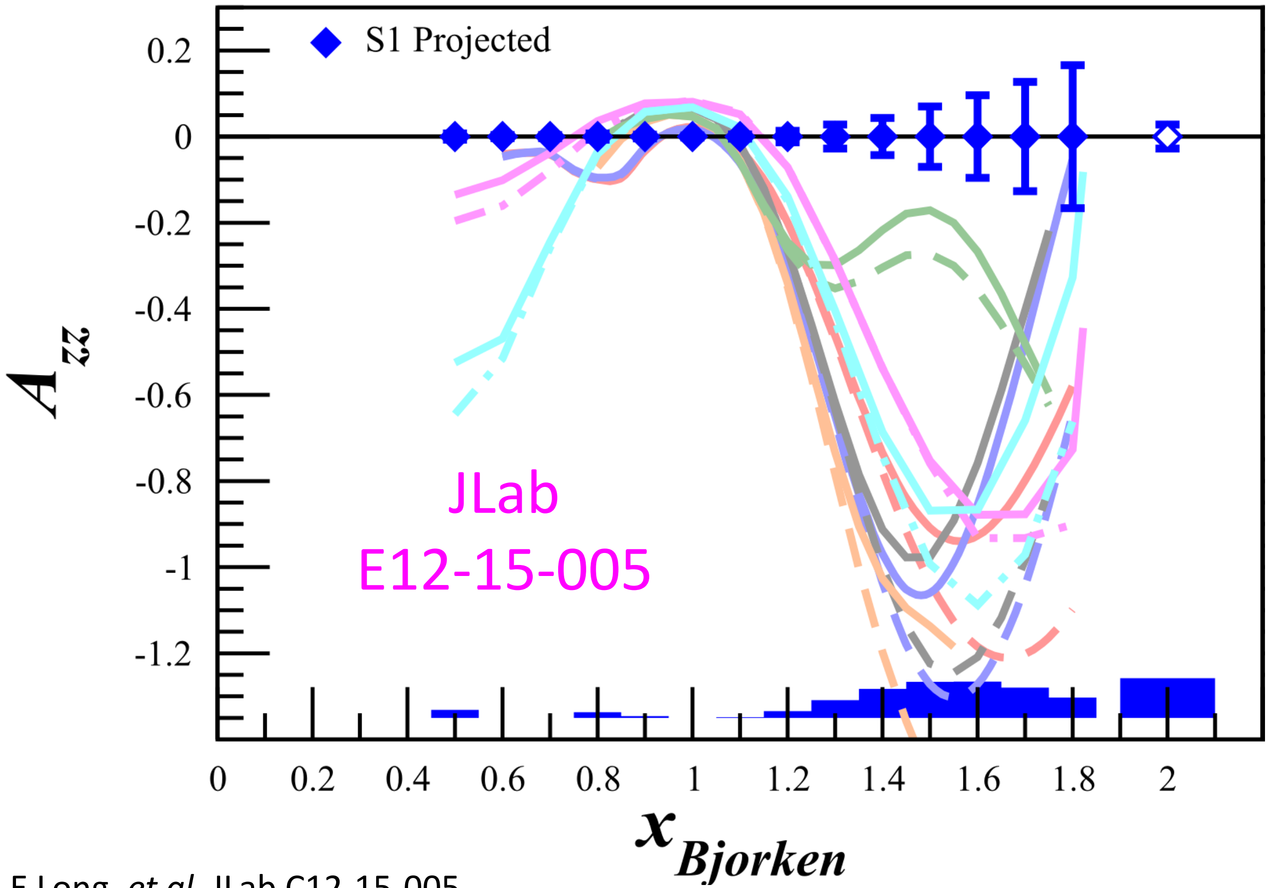

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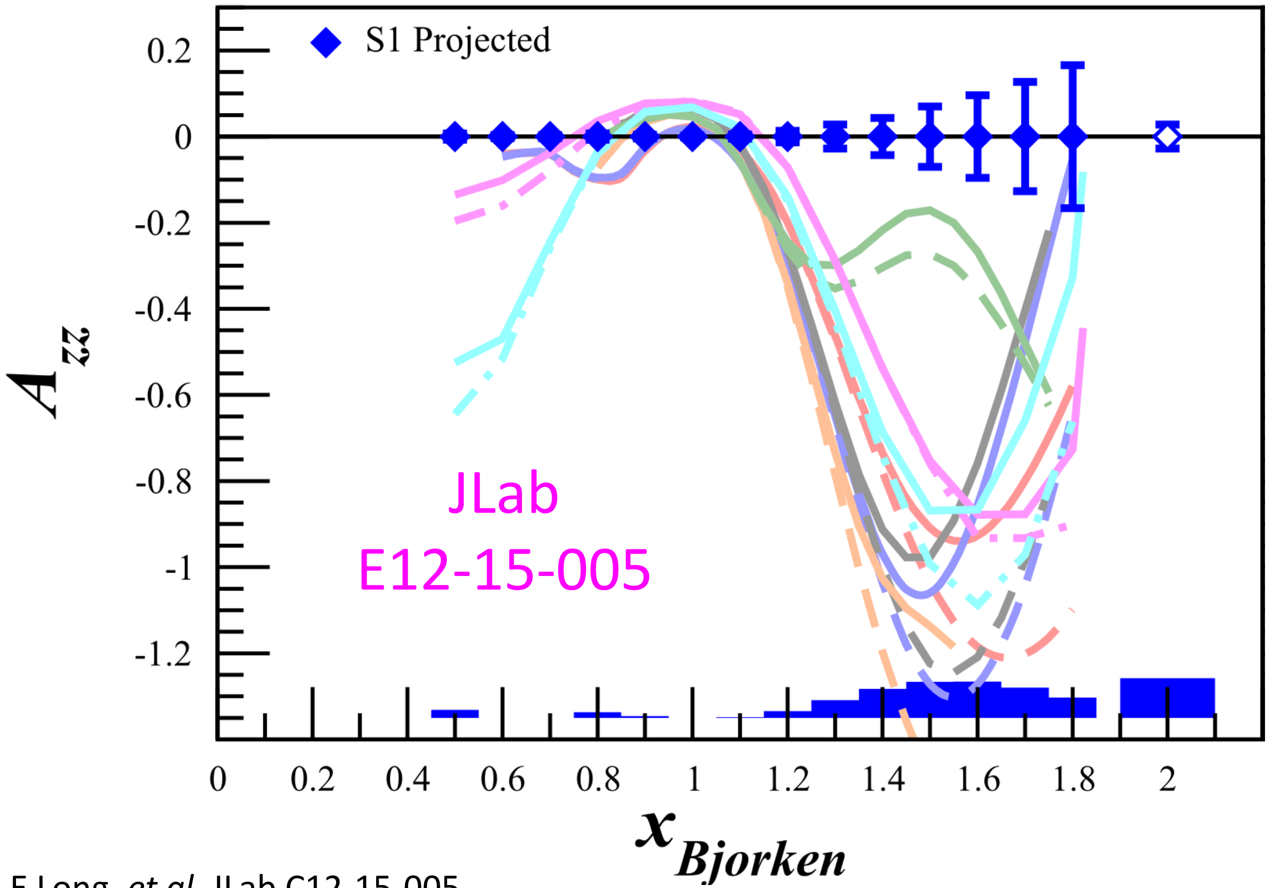

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Importance ranges from understanding **short-range correlations** to the **equations of state of neutron stars**

J. Phys.: Conf. Ser. 543 011001-012015 (2014)
http://iopscience.iop.org/1742-6596/543/1

[1] A. Bacchetta, Ph.D. Thesis (2002) arXiv:0212025

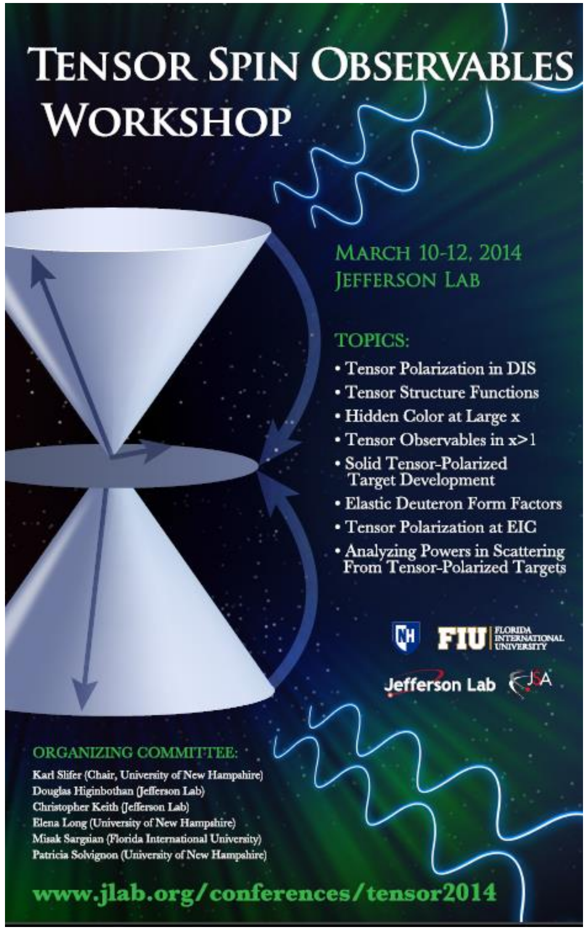
And That's Just the Beginning!

Growing tensor program:

- DIS b_1: Approved (C12-13-011)
- QE and Elastic A_{zz}: Approved (C12-15-005)
- Exotic gluon states through Δ (LOI12-16-006)

Physics accessible with a tensor polarized target:

- Orbital Angular Momentum & Spin Crisis
- Gravitomagnetic Form Factors
- Pionic Effects
- Polarized Sea Quarks
- Tensor polarized antiquarks
- Linking traditional nuclear physics and quark-gluon picture
- Final State Interactions
- Gluonic Effects
- **Tensor structure functions → b_2, b_3**
- **Tensor DVCS → Test sum rules, new helicity term**
- **Tensor Drell-Yan → 60 new structure functions**
- **Tensor TMD → Directly measure a T-odd function[1]**
- **Tensor EIC → Many calculations simplified**
- …and more!



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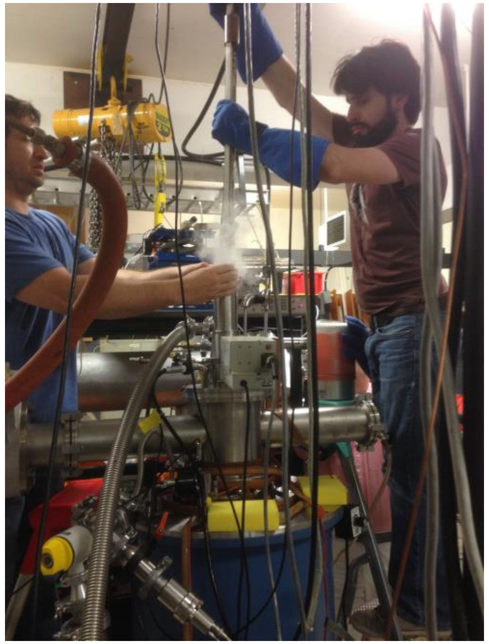

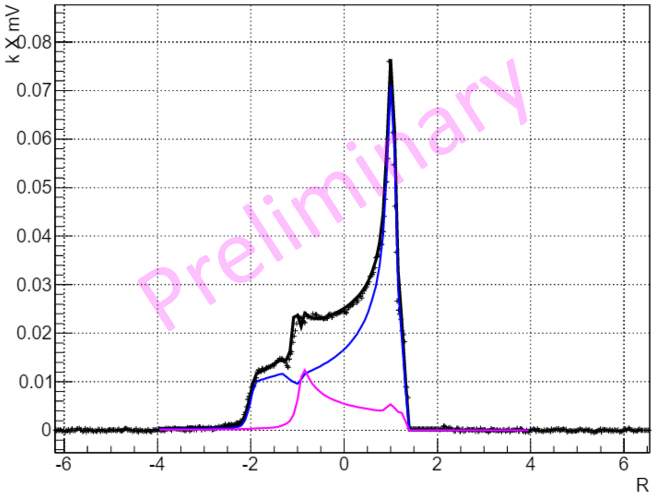

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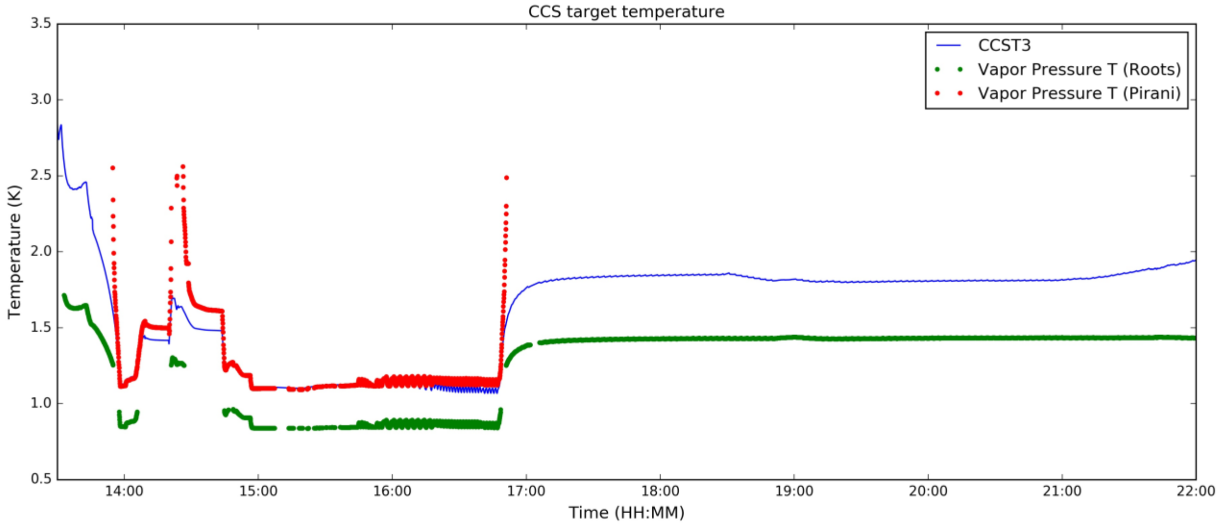

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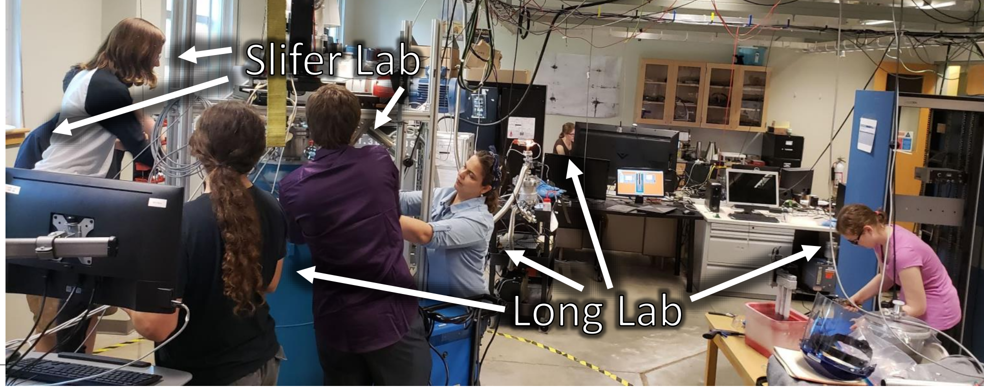

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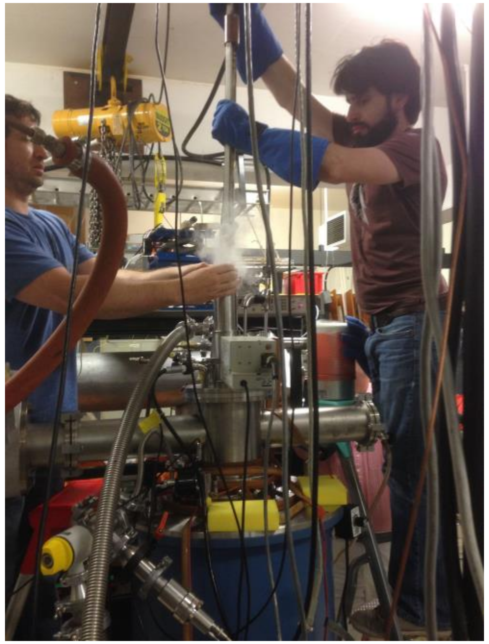

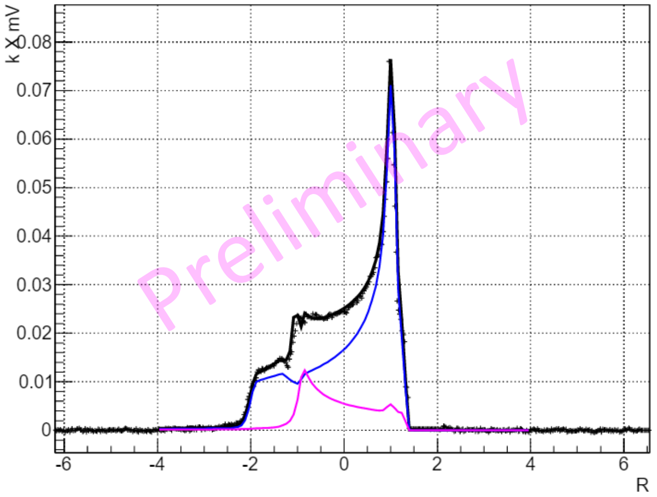

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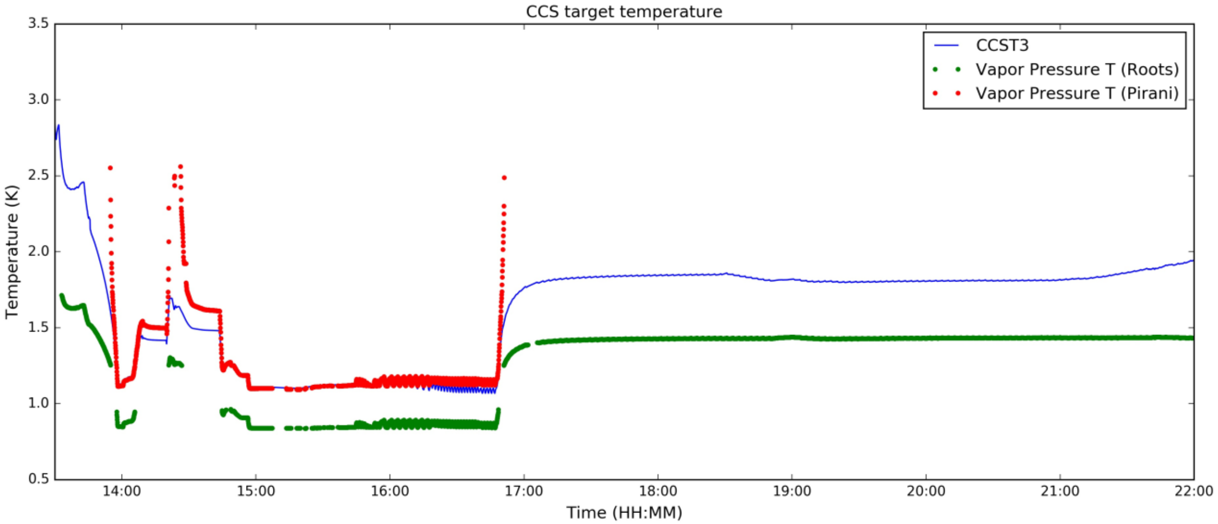

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Long Lab

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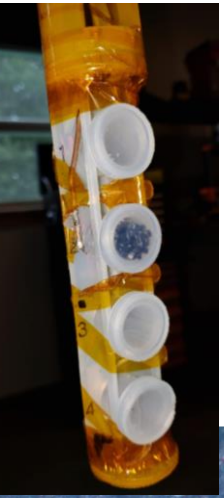

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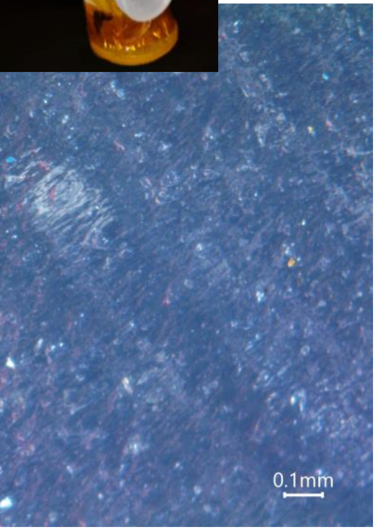

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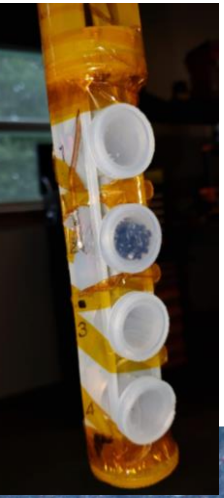

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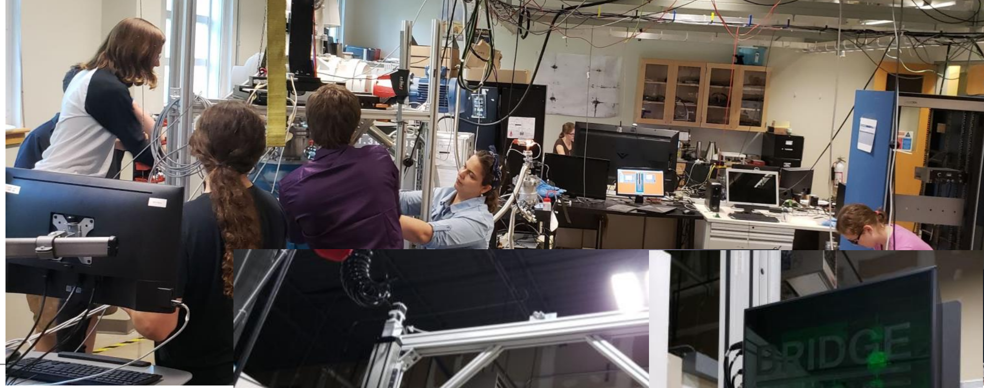

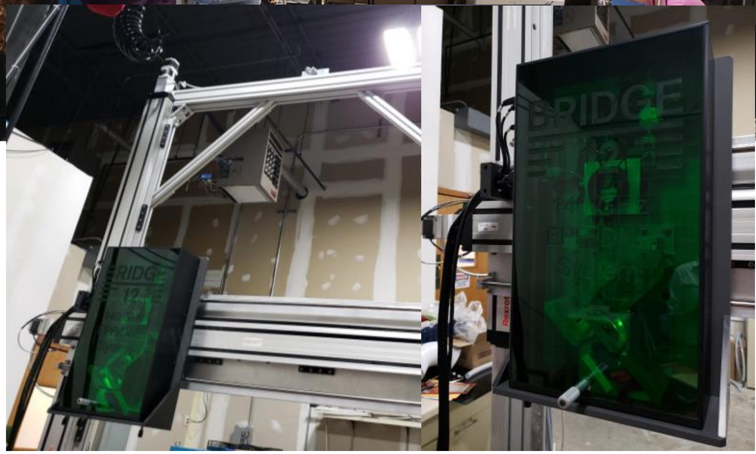

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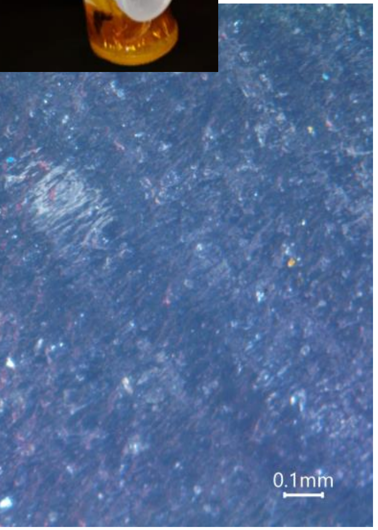

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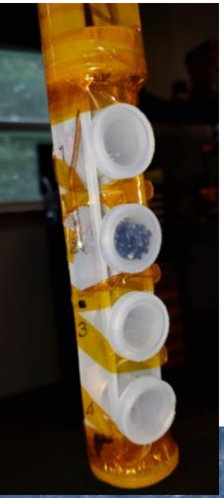

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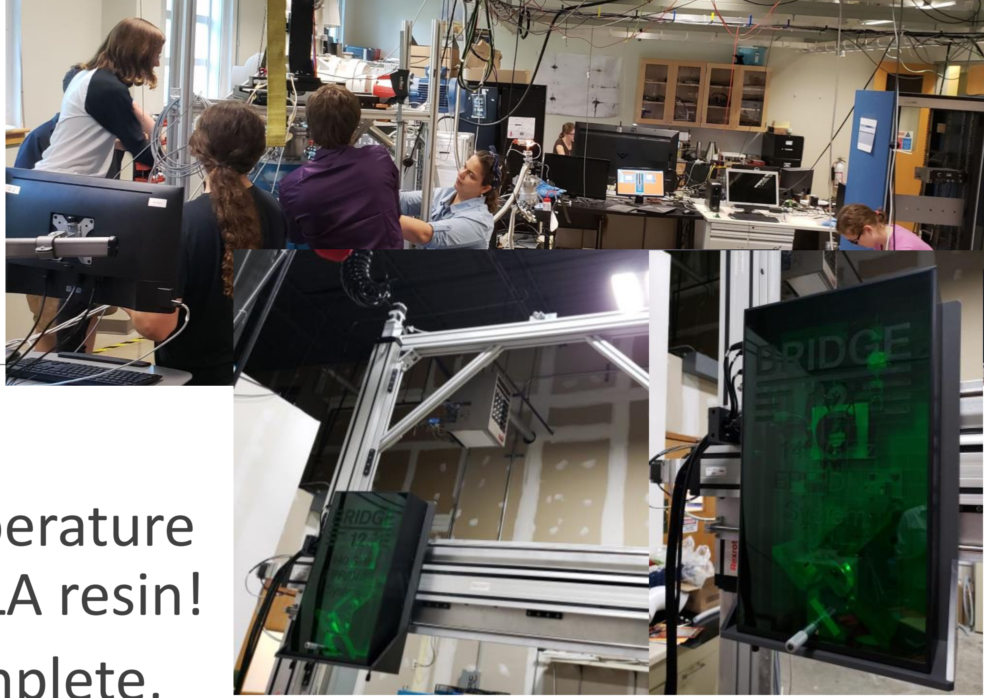

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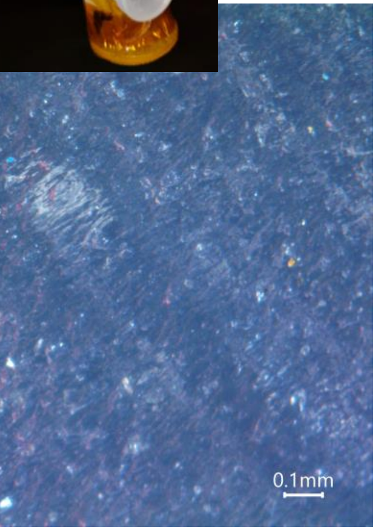

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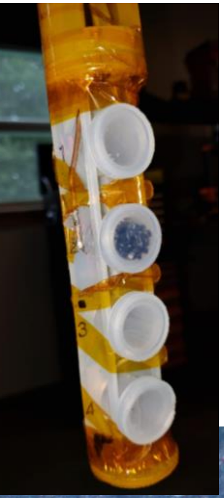

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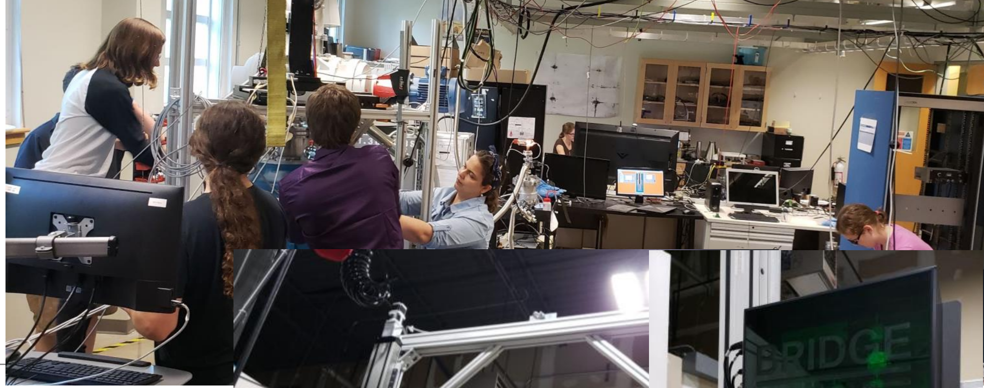

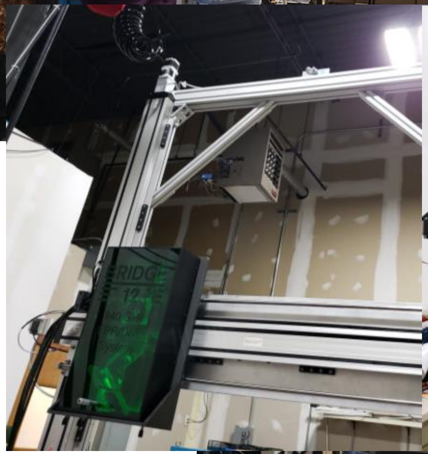

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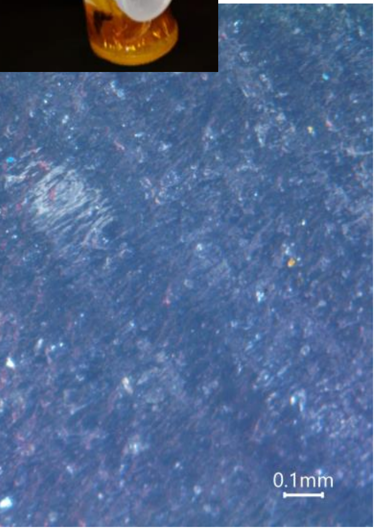

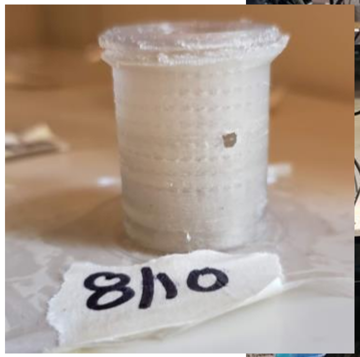

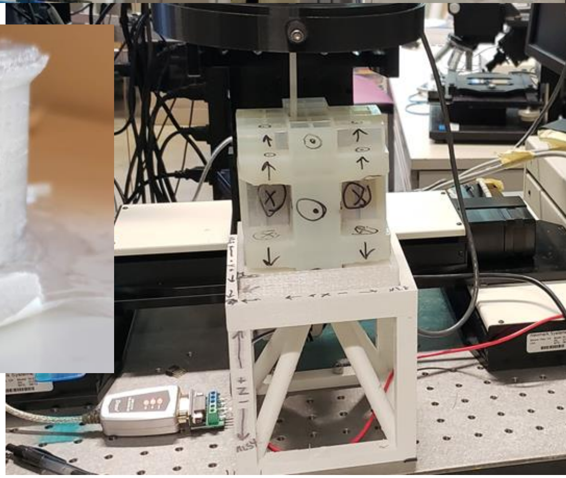

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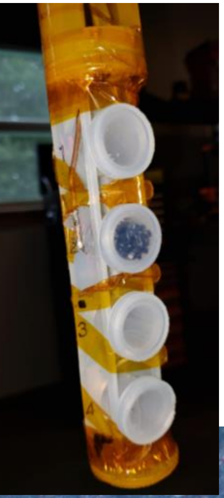

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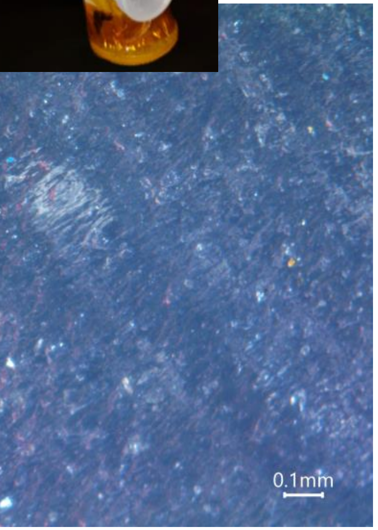

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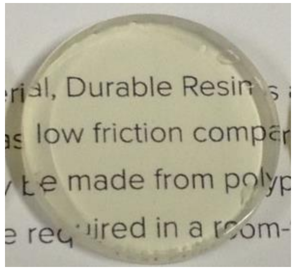

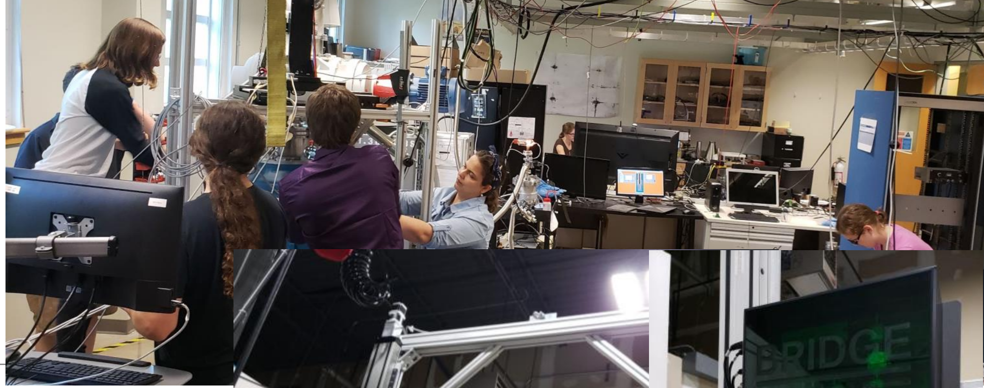

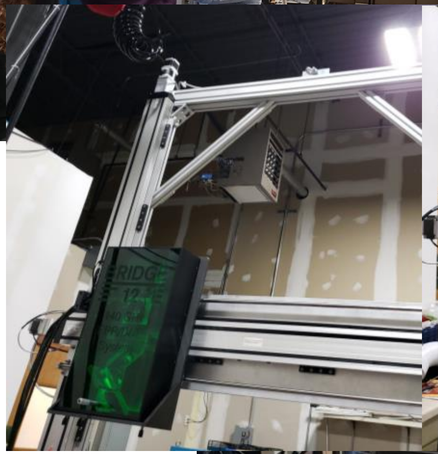

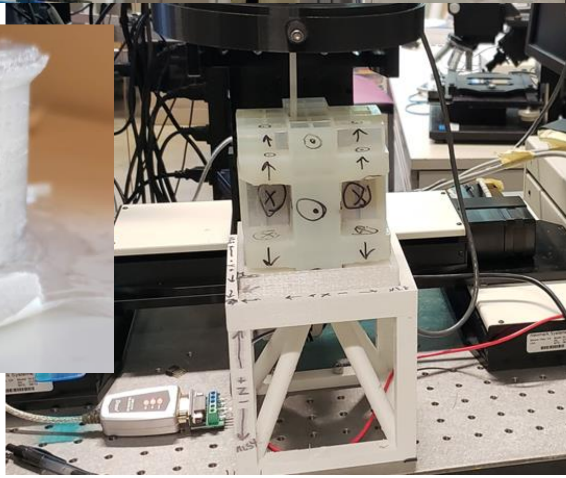

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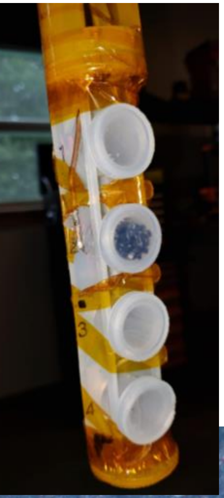

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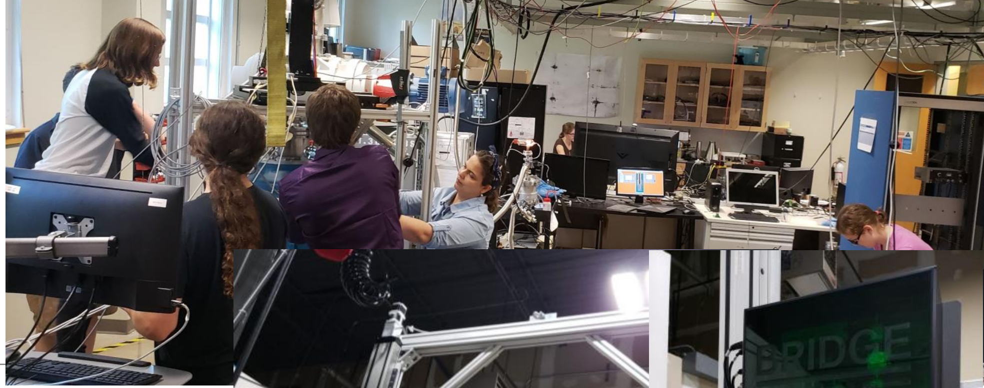
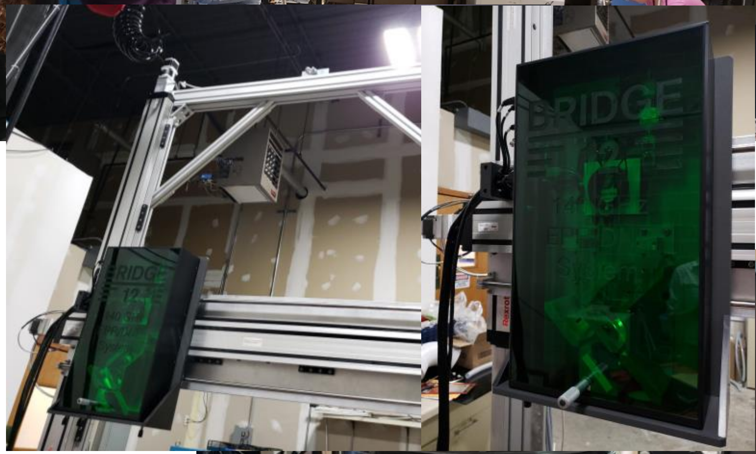
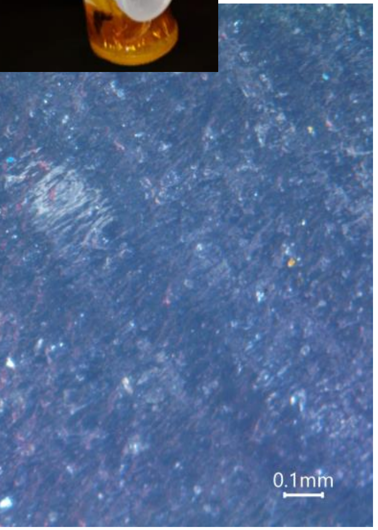
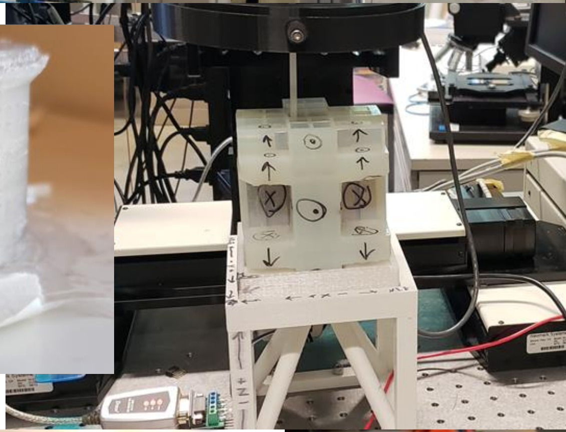


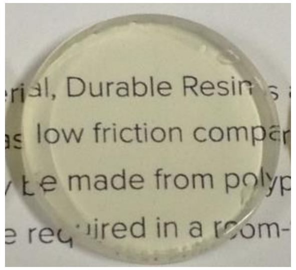


So, How Much Longer?

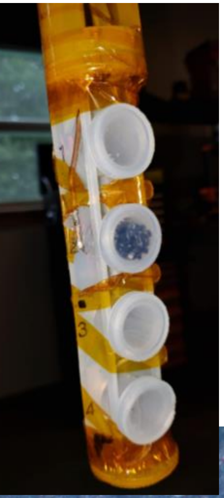


- UNH Long Lab:
  - 1st 3D-printed target stick to survive 1K temperature cycling; no microfractures w/ off-the-shelf SLA resin!
  - New solid-state mm-wave system nearly complete, capable of multiple frequencies to attempt $-P_{zz}$
  - Regularly printing with FEP, first 3D printed Kel-F target cup on Aug. 30
  - Debugging NMR systems with novel 0.8 T Halbach
  - Starting to 3D print tiny scintillators for low-energy scattering/proof of P_{zz}
  - Attempting to 3D print 10 MeV beamline for target material pre-irradiation with <$4k printer





After 1K



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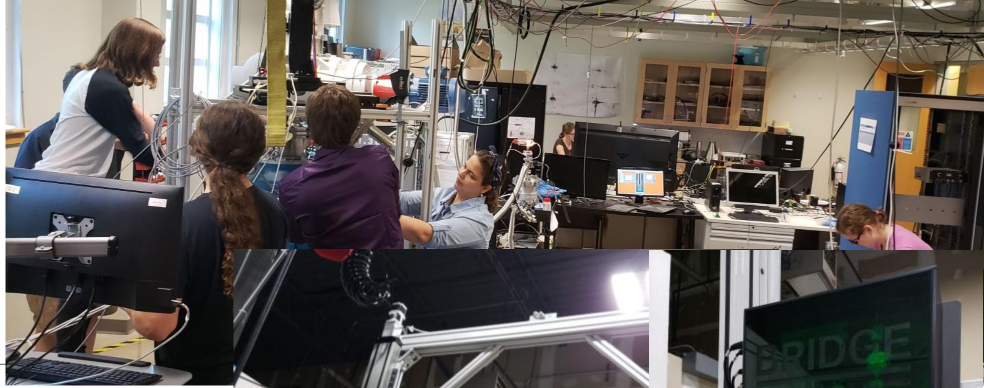
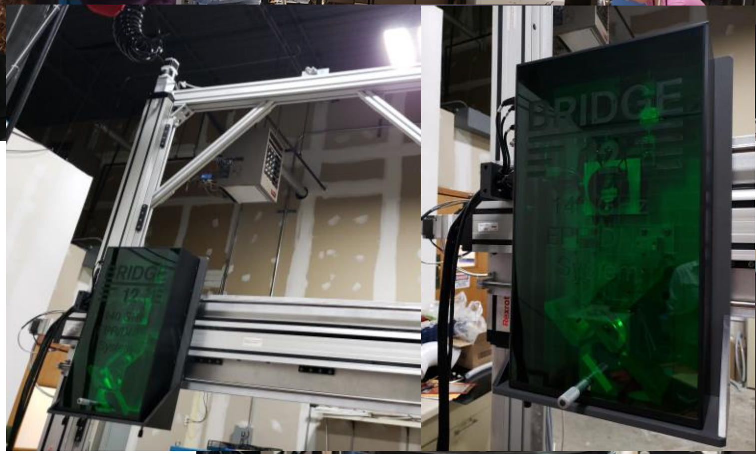
Long Lab

All This in ~ 1 Year

So, How Much Longer?





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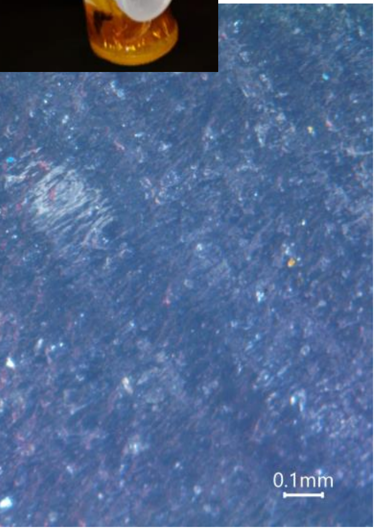
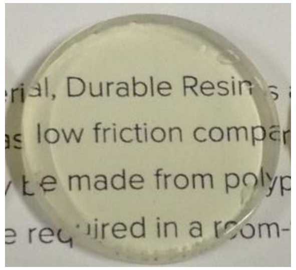
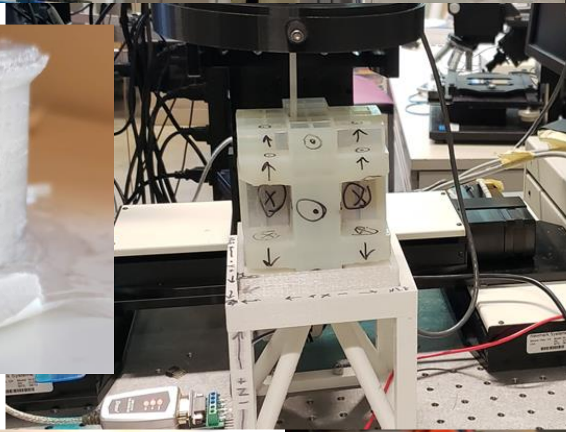
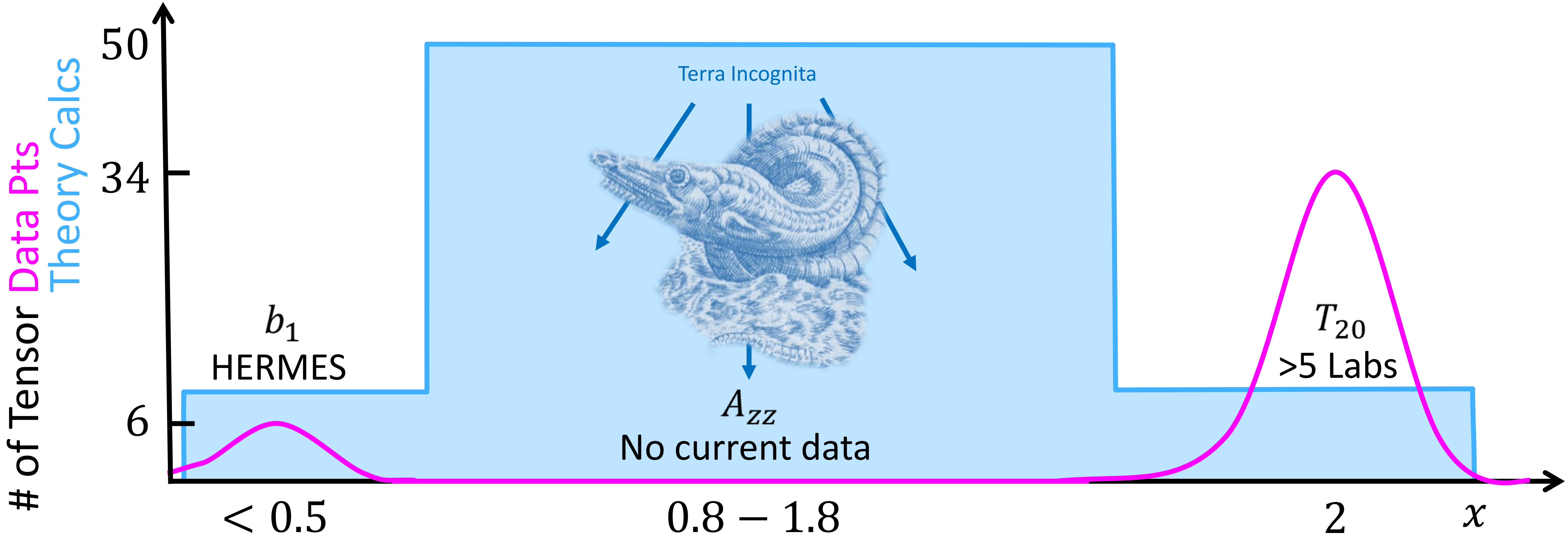


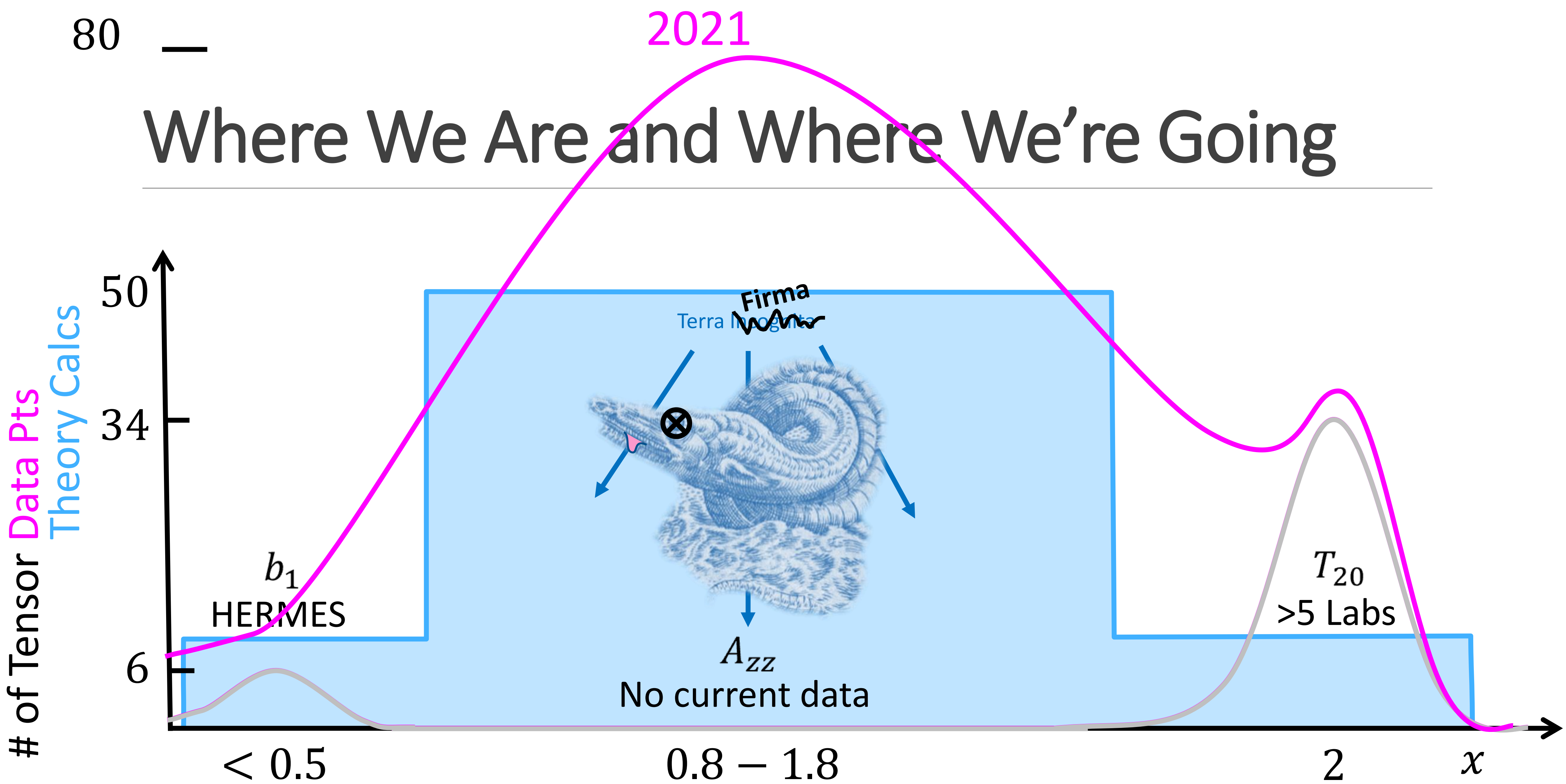




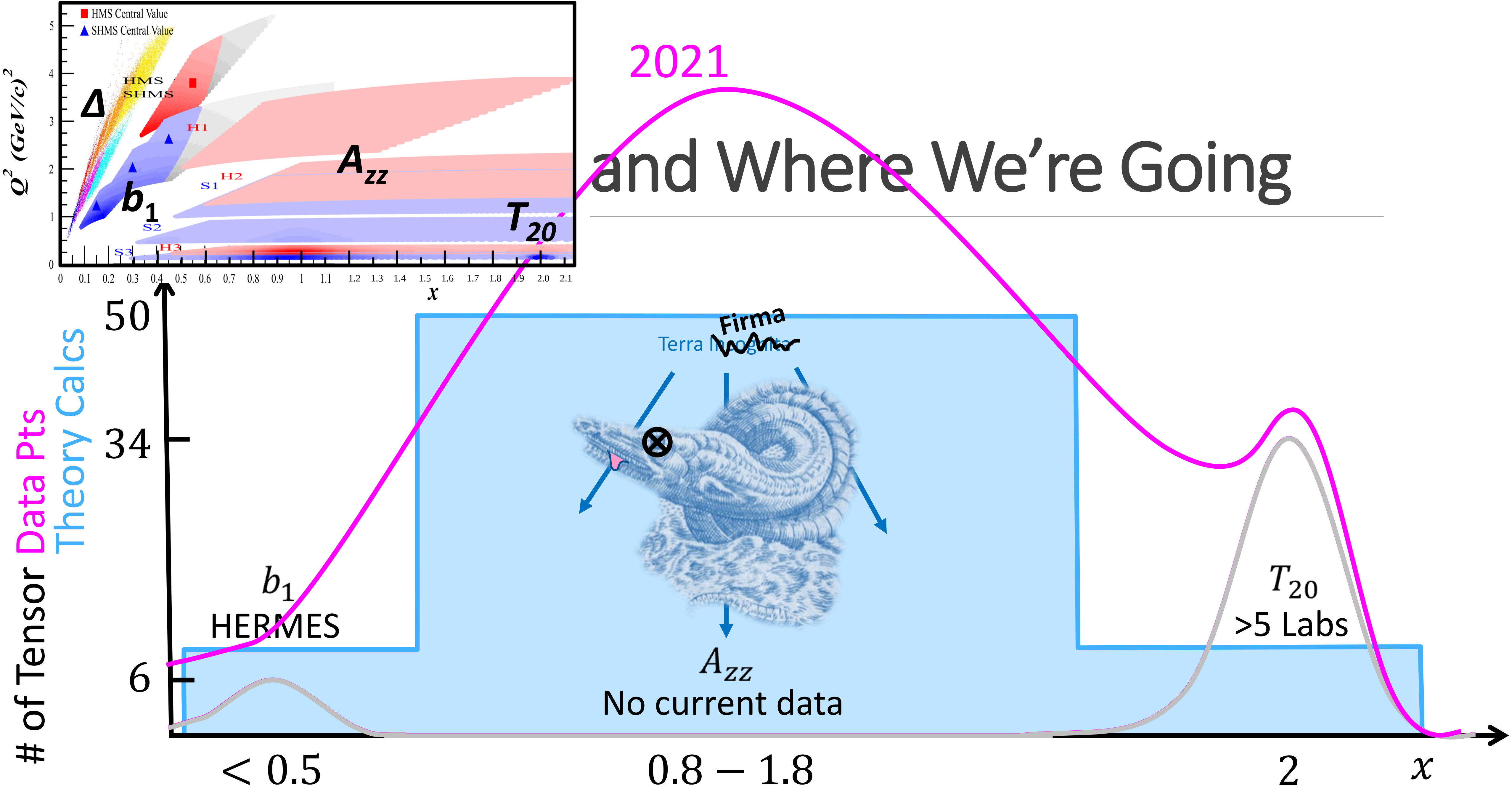
Where We Are and Where We're Going



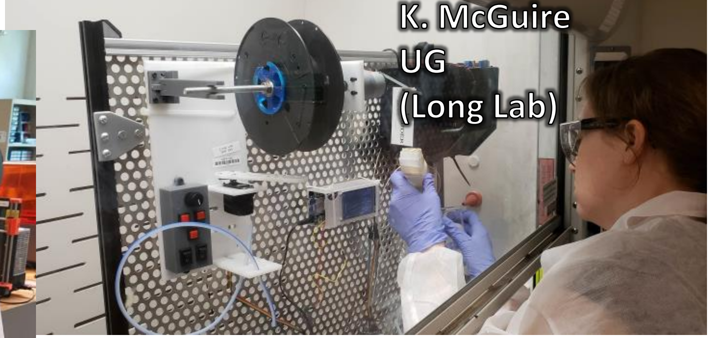
Where We Are and Where We're Going

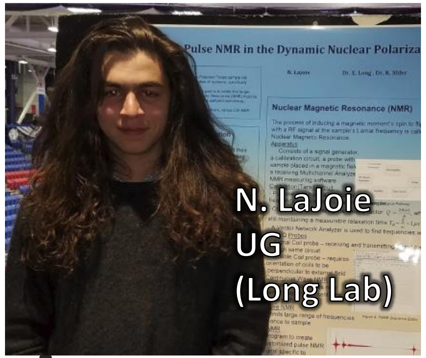


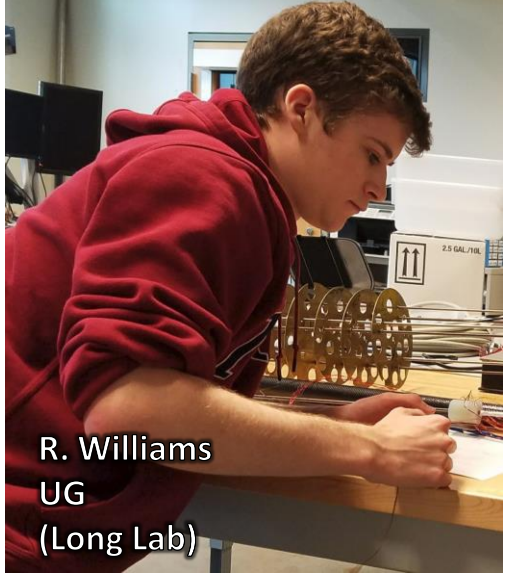
and Where We're Going

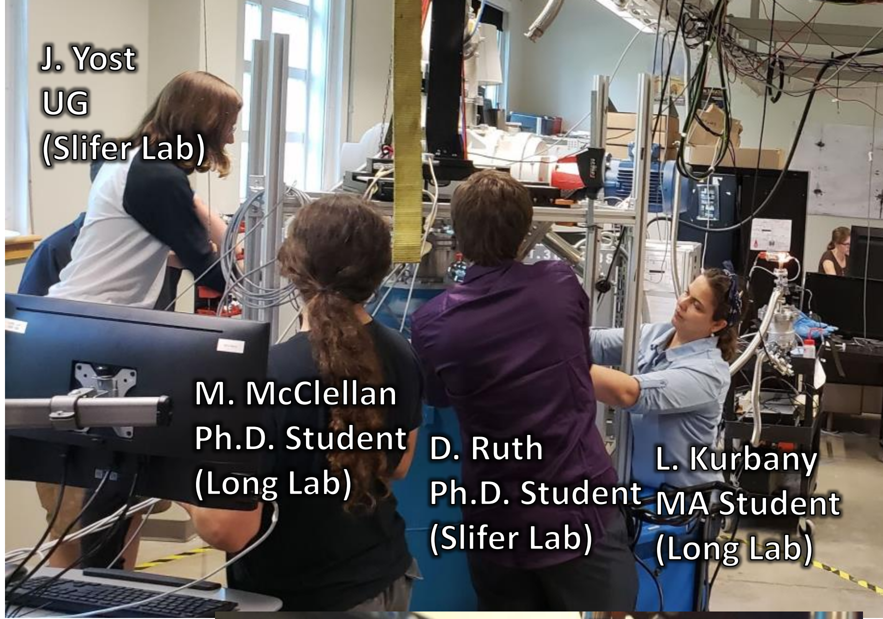



E. Granok
UG
(Long Lab)


K. McGuire
UG
(Long Lab)


Pulse NMR in the Dynamic Nuclear Polariza
Nuclear Magnetic Resonance (NMR)
N. LaJoie
UG
(Long Lab)

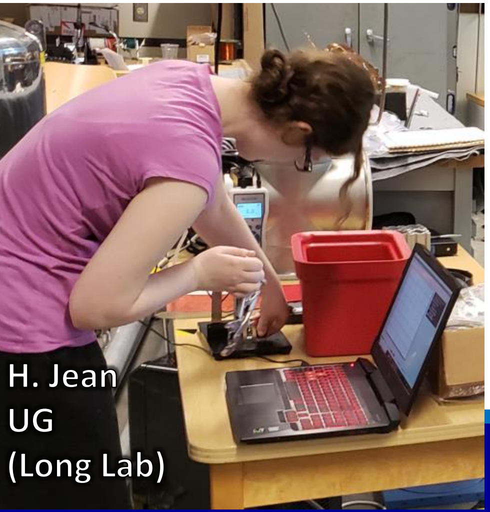

R. Williams
UG
(Long Lab)

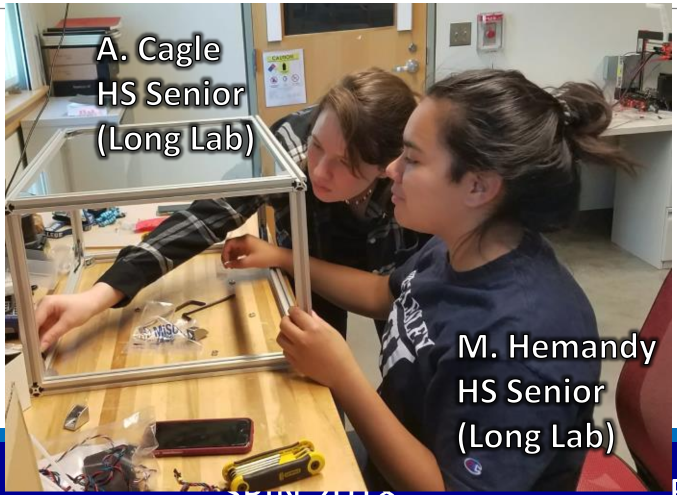

J. Yost
UG
(Slifer Lab)
M. McClellan
Ph.D. Student
(Long Lab)
D. Ruth
Ph.D. Student
(Slifer Lab)
L. Kurbany
MA Student
(Long Lab)

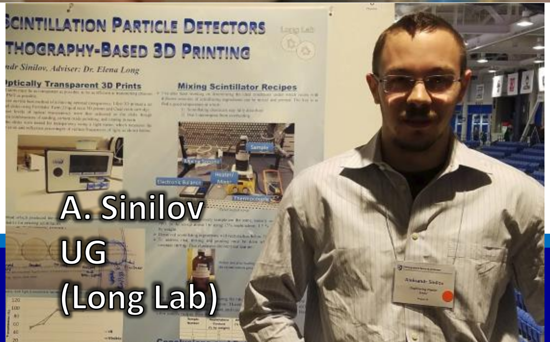
Thank you!


K. Slifer


N. Santiesteban
Ph.D. Student
(Slifer Lab)


H. Jean
UG
(Long Lab)


A. Cagle
HS Senior
(Long Lab)
M. Hemandy
HS Senior
(Long Lab)


SCINTILLATION PARTICLE DETECTORS
THOGRAPHY-BASED 3D PRINTING
A. Sinilov
UG
(Long Lab)

Backup Slides

A_{zz} and T_{20}

C12-15-005: Quasi-Elastic and Elastic Deuteron Tensor Asymmetries

C1-Approved, A- Physics Rating

Spokespeople:

E. Long*, K. Slifer, P. Solvignon, D. Day, D. Keller,

D. Higinbotham

“There is a strong need for models of the deuteron wave function that are both realistic and **relativistic**.” - J. Terry, G. Miller, arXiv:1603.07032 (2016)

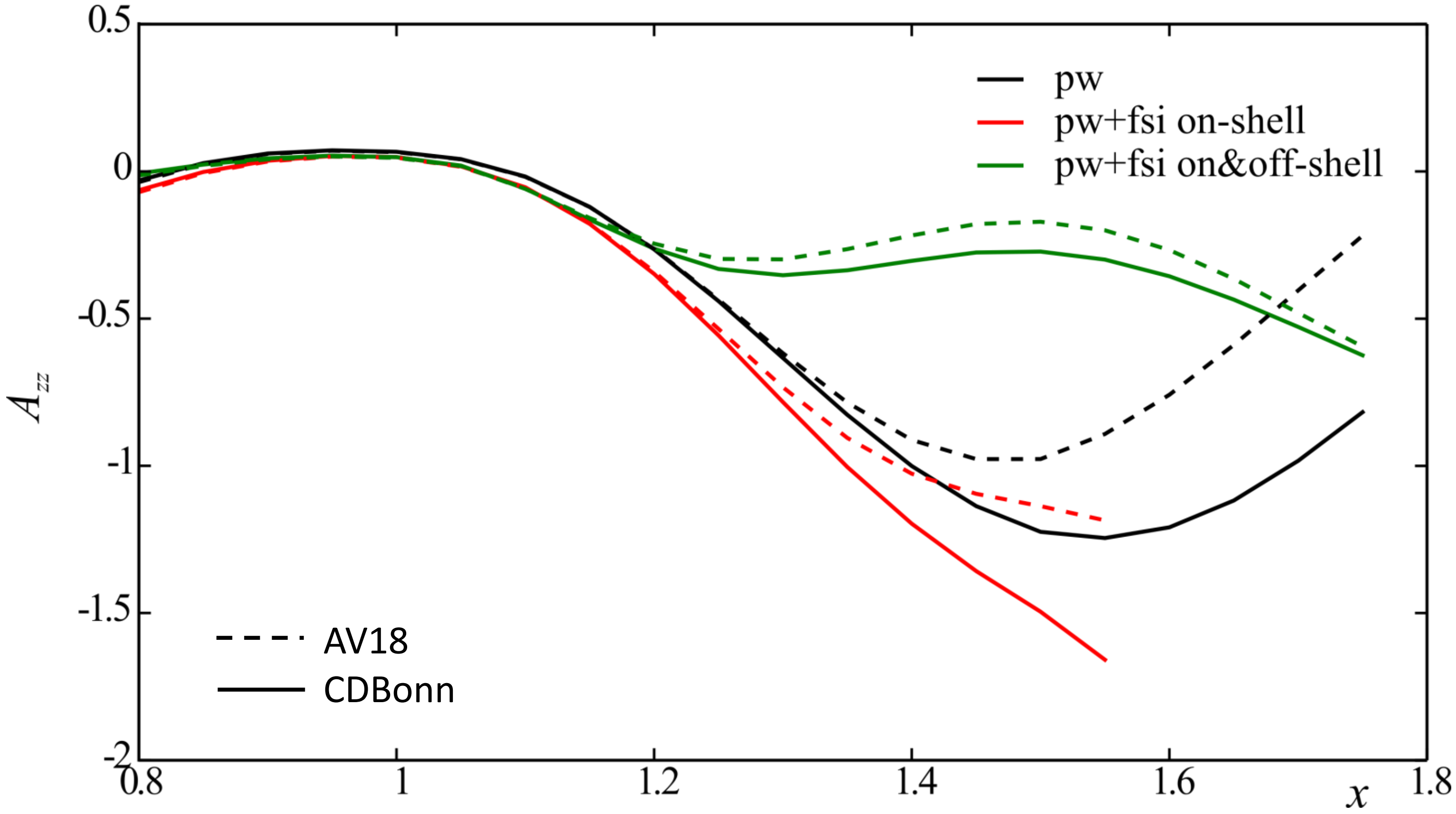
Final State Interactions

FSI must be understood & minimized to get *NN* potential information

Minimum/maximum FSI on A_{zz} calculated by W. Cosyn[1]

FSIs minimized in kinematic choice (large $x \geq 1.35$ and medium p_m)

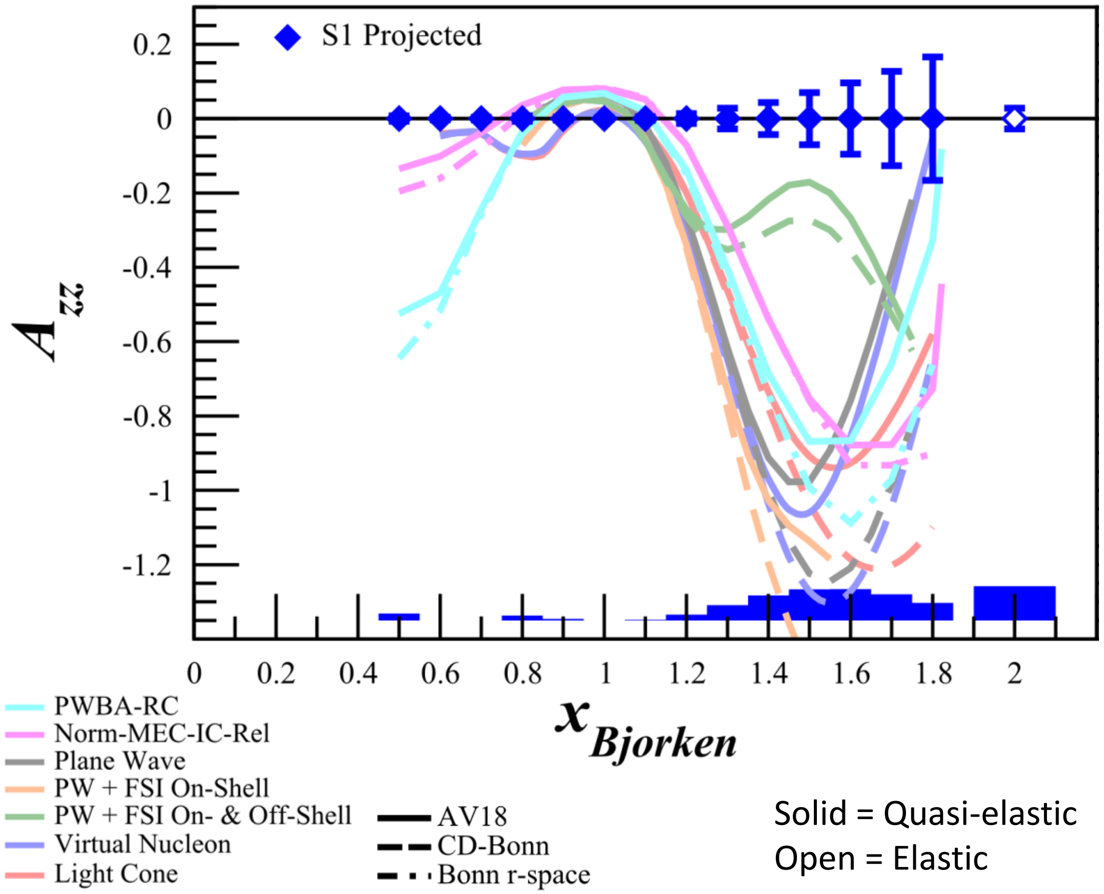
- Best suited for attempting to extract information on *D*-wave content[2]



[2] S Jeschonnek, JW Van Orden, arXiv:1606.04072 (2016)

[1] W Cosyn

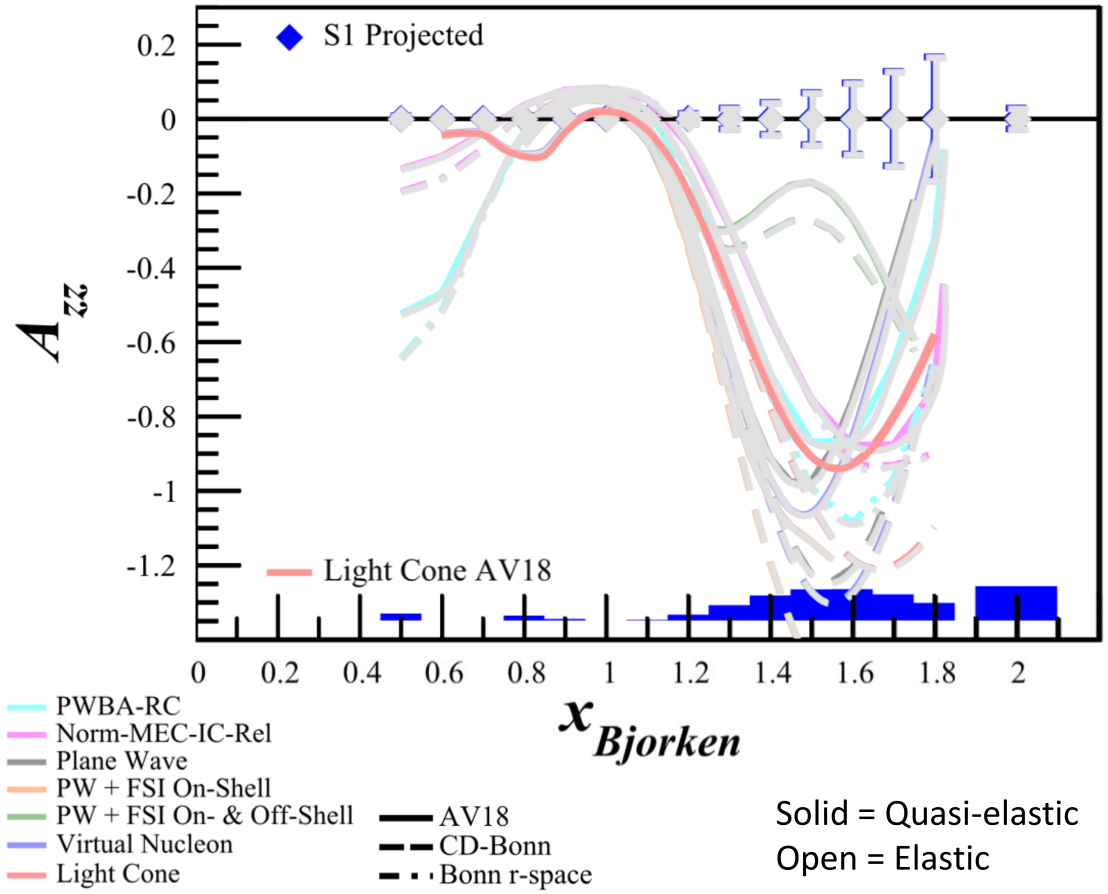
Discriminating Power



Solid = Quasi-elastic
Open = Elastic

E Long, *et al*, JLab C12-15-005

Discriminating Power



$- LC_{AV18} =$

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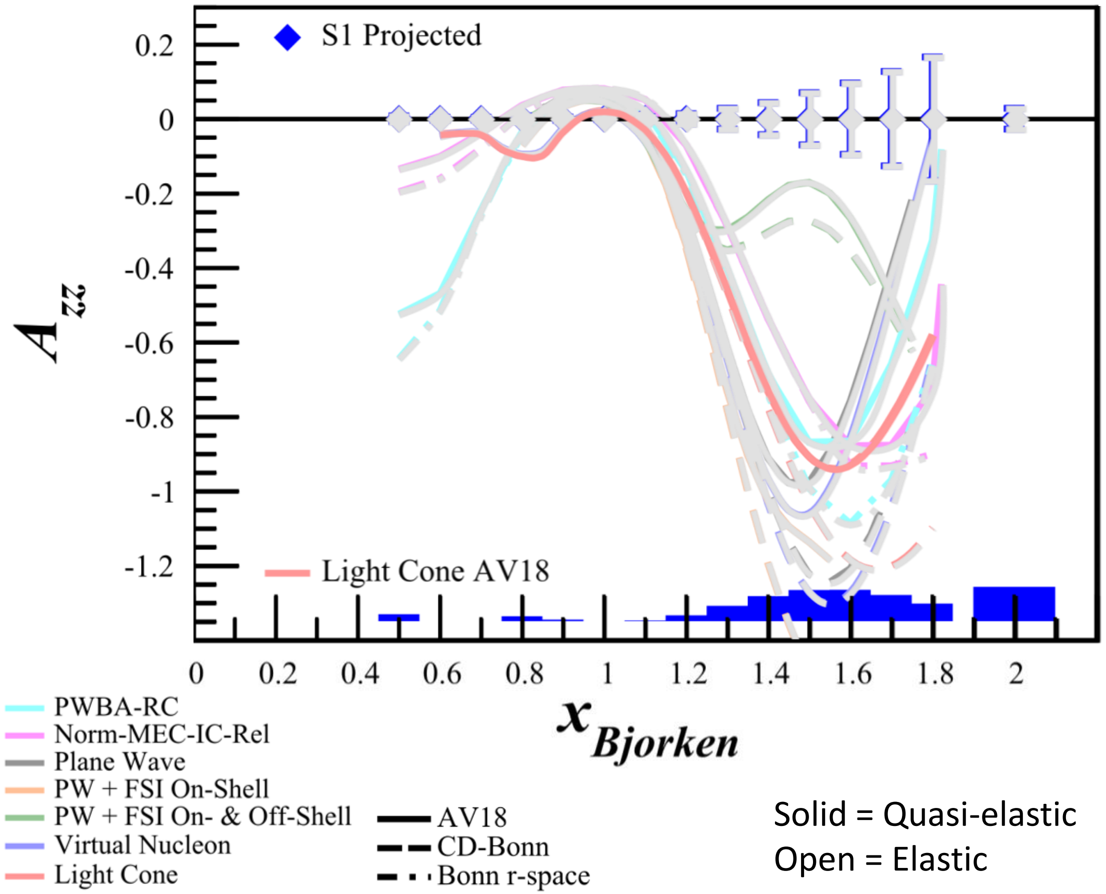
Open = Elastic

E Long, *et al*, JLab C12-15-005

Discriminating Power



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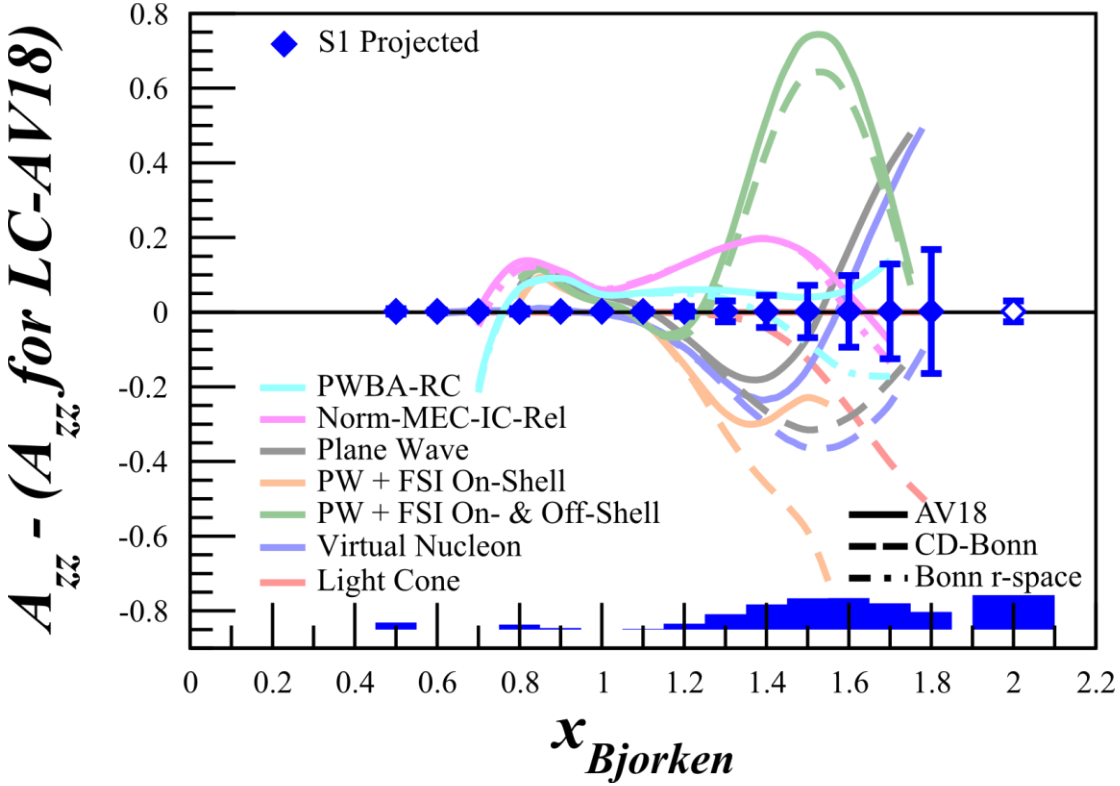

Solid = Quasi-elastic
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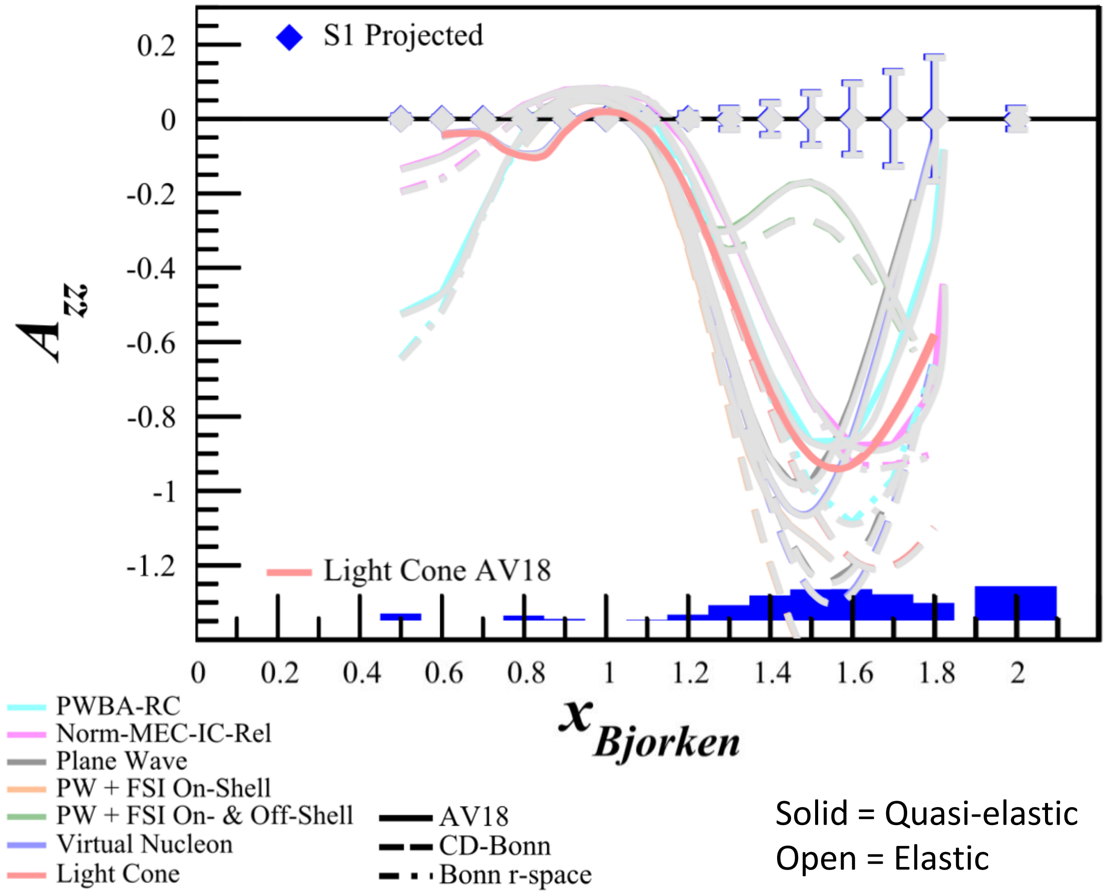
E Long, *et al*, JLab C12-15-005

Discriminating Power



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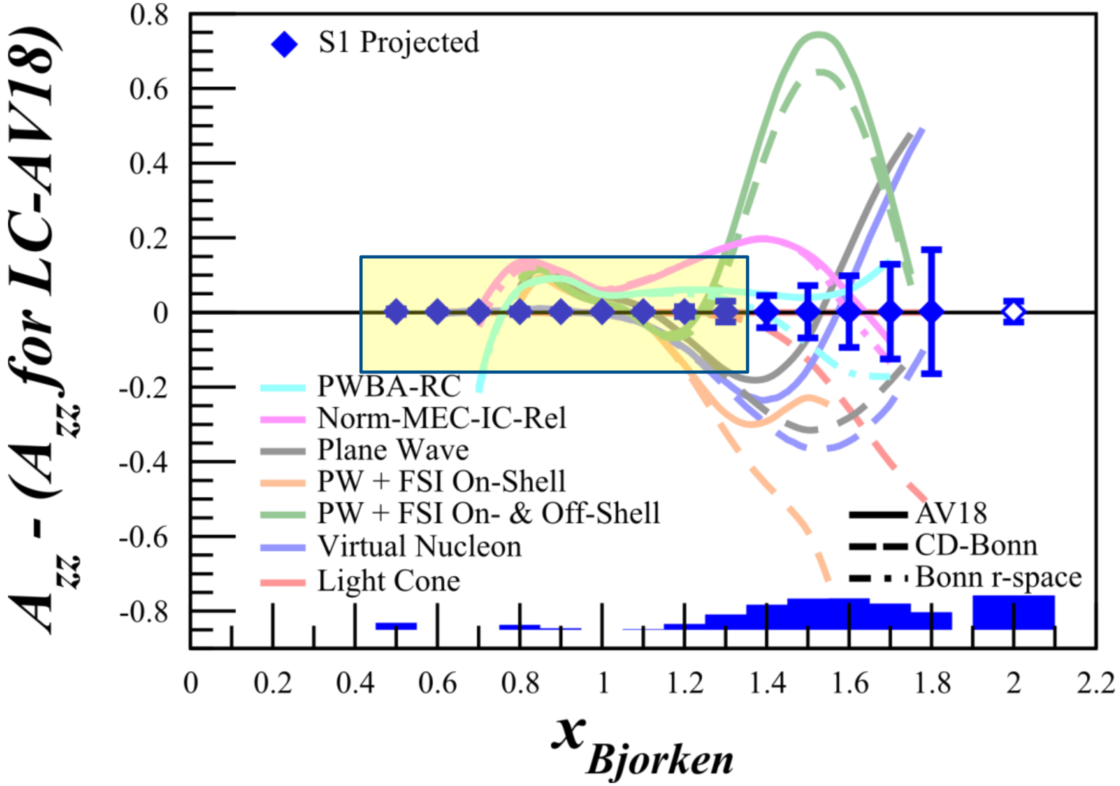
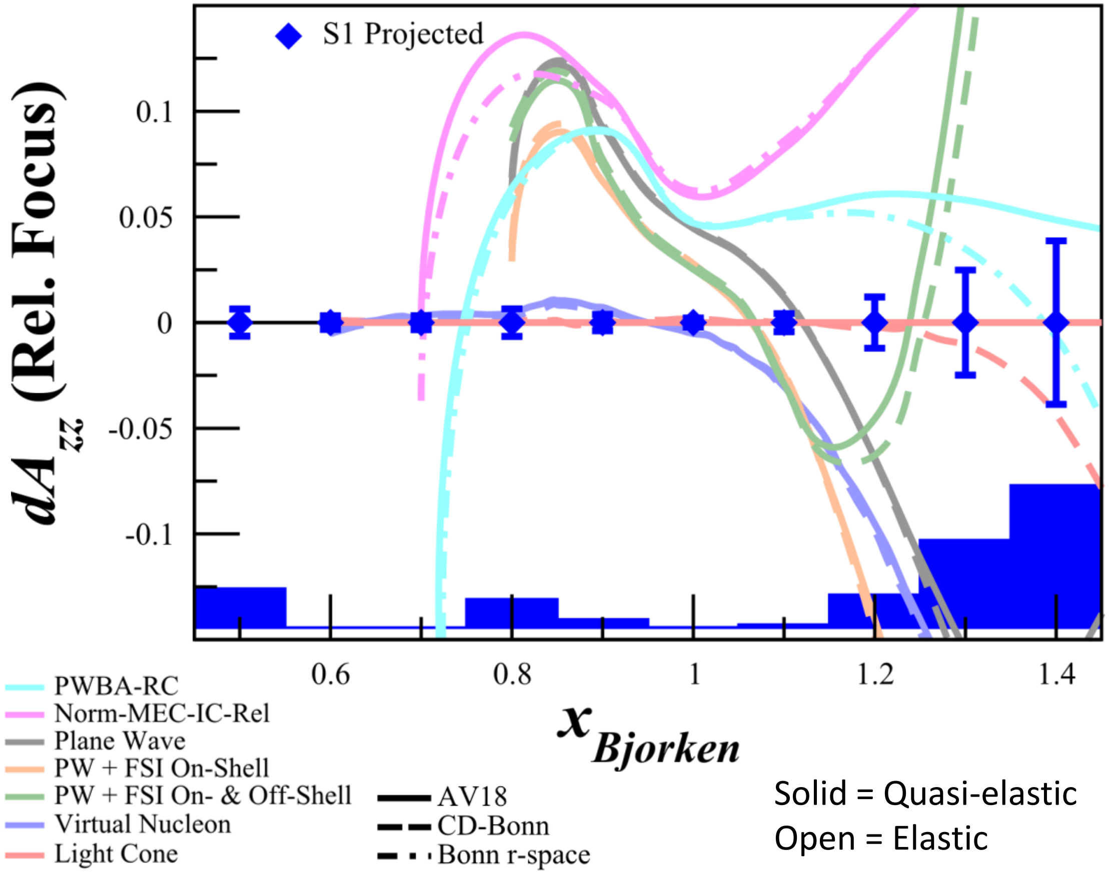


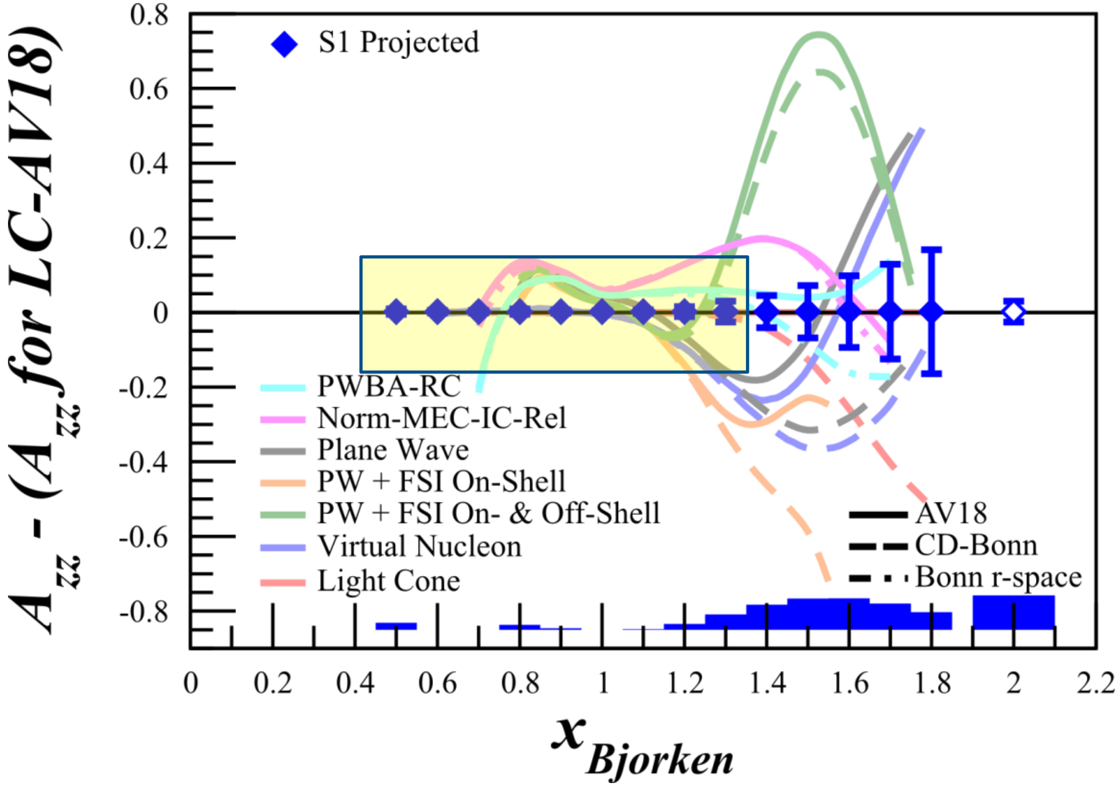
Solid = Quasi-elastic
Open = Elastic

E Long, *et al*, JLab C12-15-005

Discriminating Power

Relativistic Model Discrimination **>6σ**





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E Long, *et al*, JLab C12-15-005

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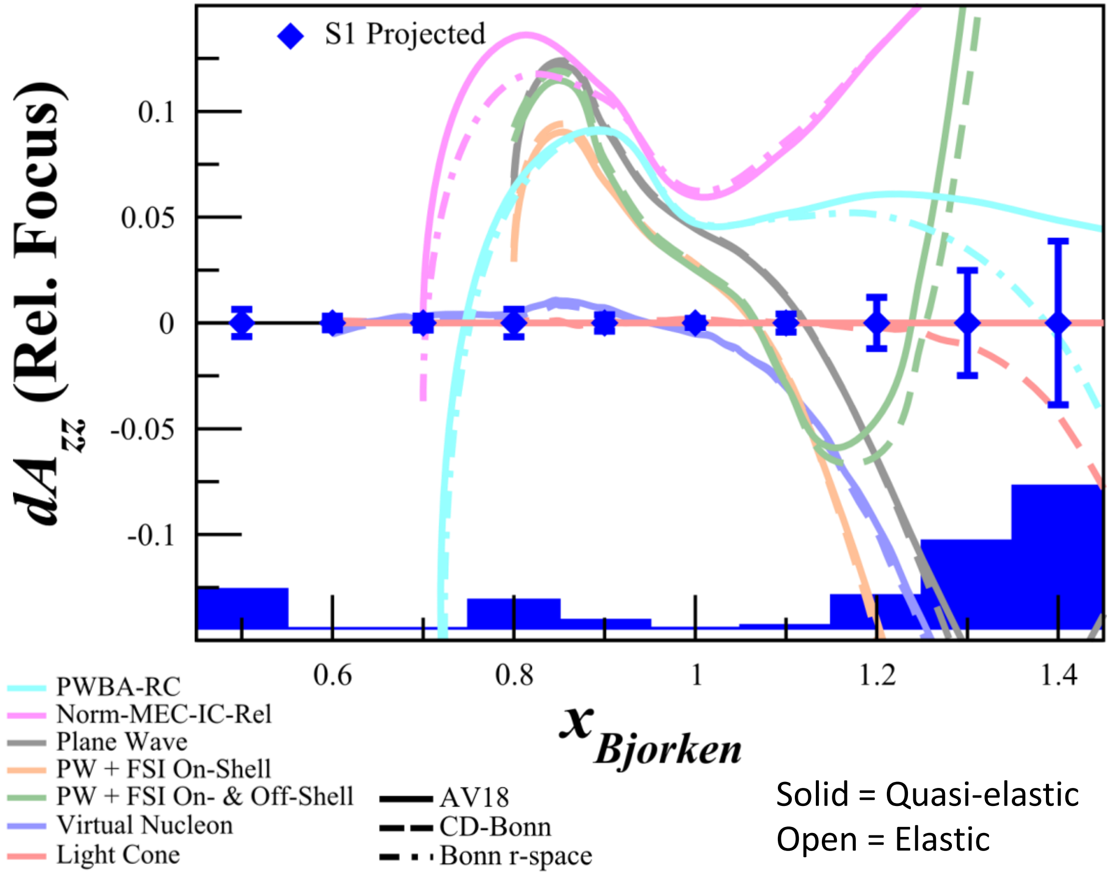

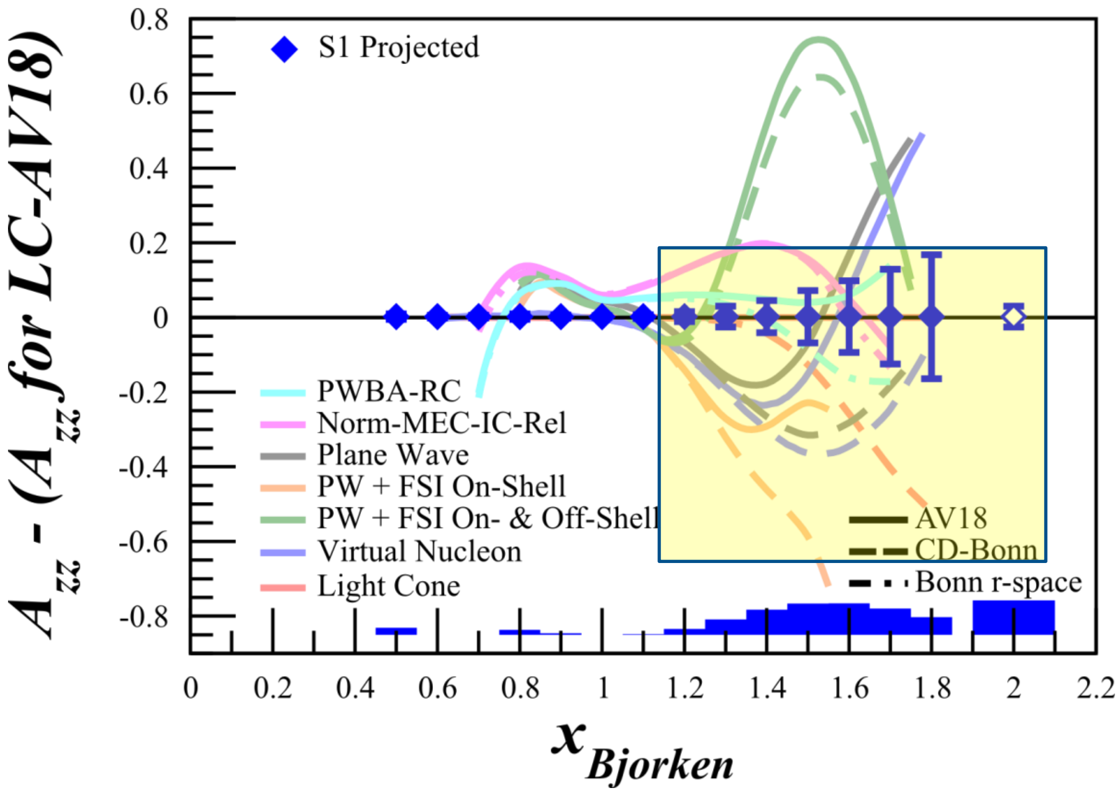

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Discriminating Power

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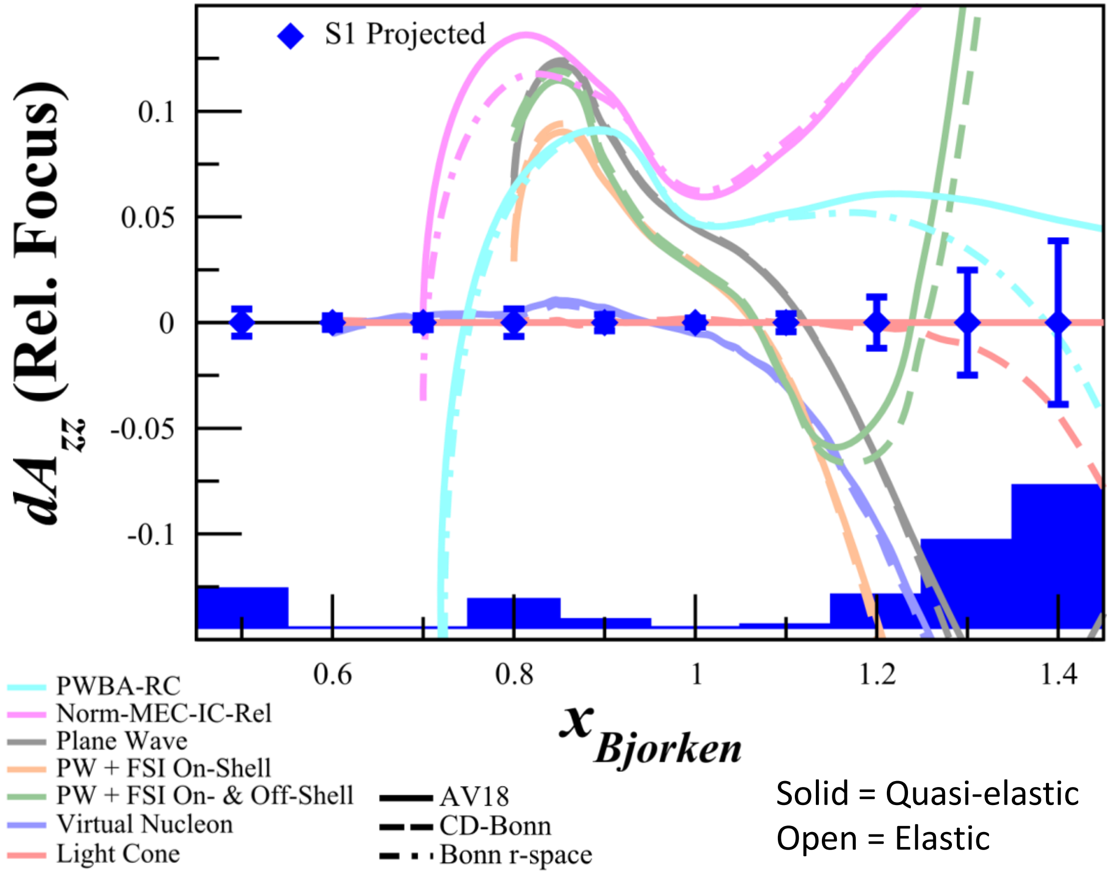
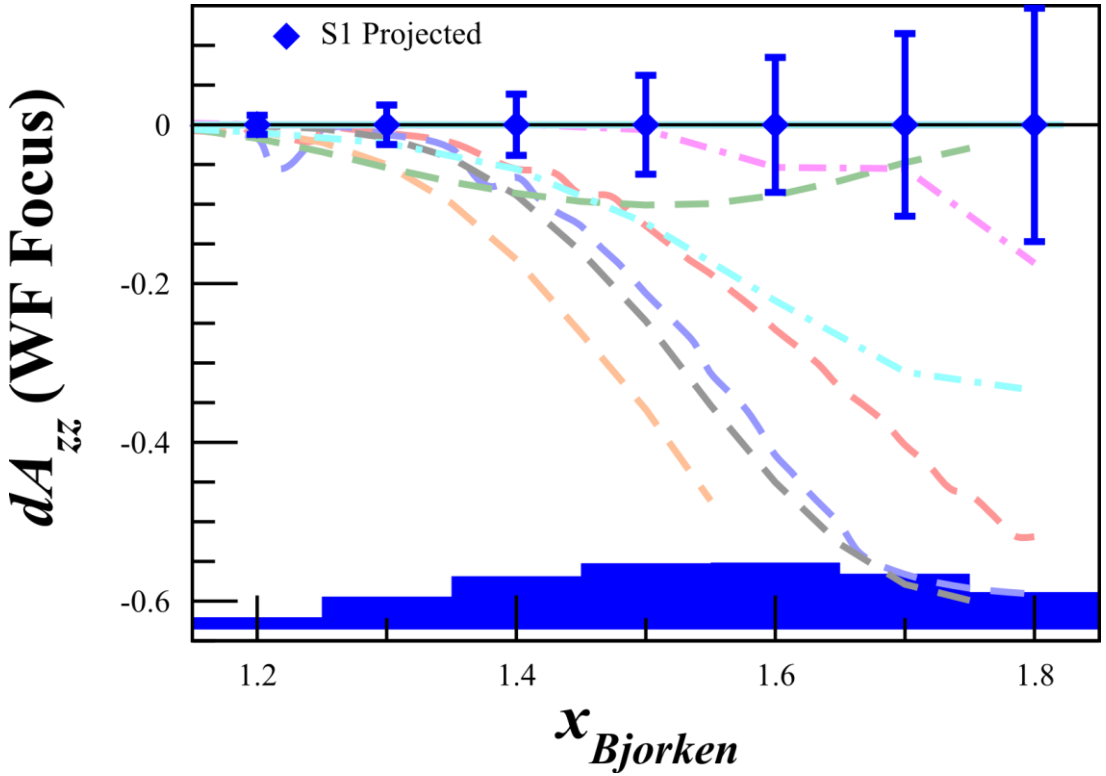


Wave Function Discrimination up to **>4σ**



Solid = Quasi-elastic
Open = Elastic

E Long, *et al*, JLab C12-15-005

b_1

C12-13-011: The Deuteron Tensor Structure Function b_1

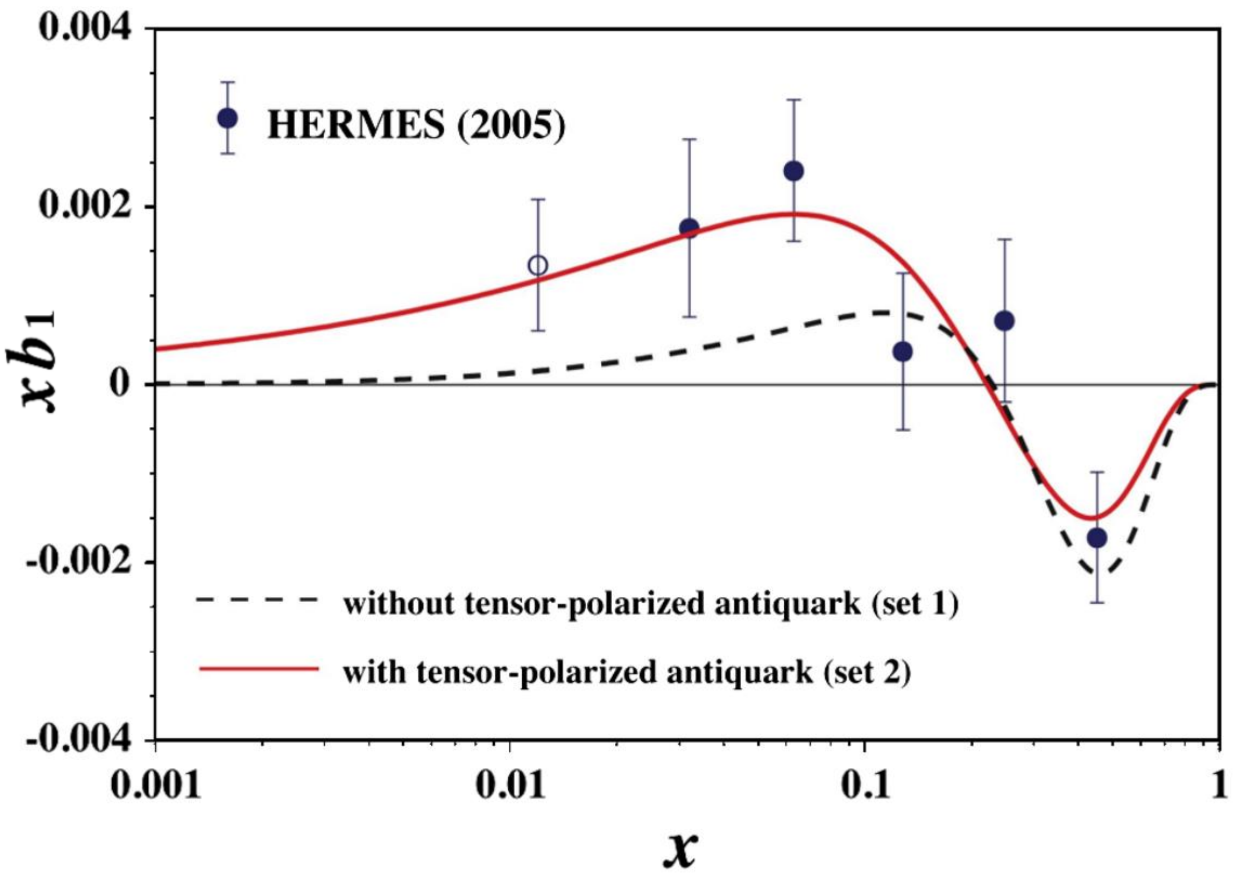
C1-Approved, A- Physics Rating

Spokespeople:

K. Slifer*, O.R. Aramayo, J.P. Chen, N. Kalatarians, D. Keller, E. Long, P. Solvignon

Sea Quark Polarization

- $b_1 = \frac{1}{36}\delta_T w[5\{u_v + d_v\}]$ Quarks
  $+4\alpha_{\bar{q}}[2\bar{u} + 2\bar{d} + s + \bar{s}]$ Sea Strange & Anti-Quarks
- Looked at $\alpha_{\bar{q}} = 0$ and floating $\alpha_{\bar{q}}$
  - $\alpha_{\bar{q}} \sim$ Polarization of sea
- $\alpha_{\bar{q}} = 3.20 \pm 0.212$ improved χ^2
- Indicates significant tensor polarization in antiquark distributions



S Kumano, PRD **82** 017501 (2010)

6-Quark, Hidden Color

- Deuteron wave function can be expressed as
  - $|6q\rangle = \sqrt{\frac{1}{9}}|NN\rangle + \sqrt{\frac{4}{45}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|CC\rangle$

Nucleon-Nucleon

Delta-Delta

Hidden Color

- Early hidden color calculations gave small results, but author noted "as experimental techniques have improved dramatically, the meaning of small has changed."

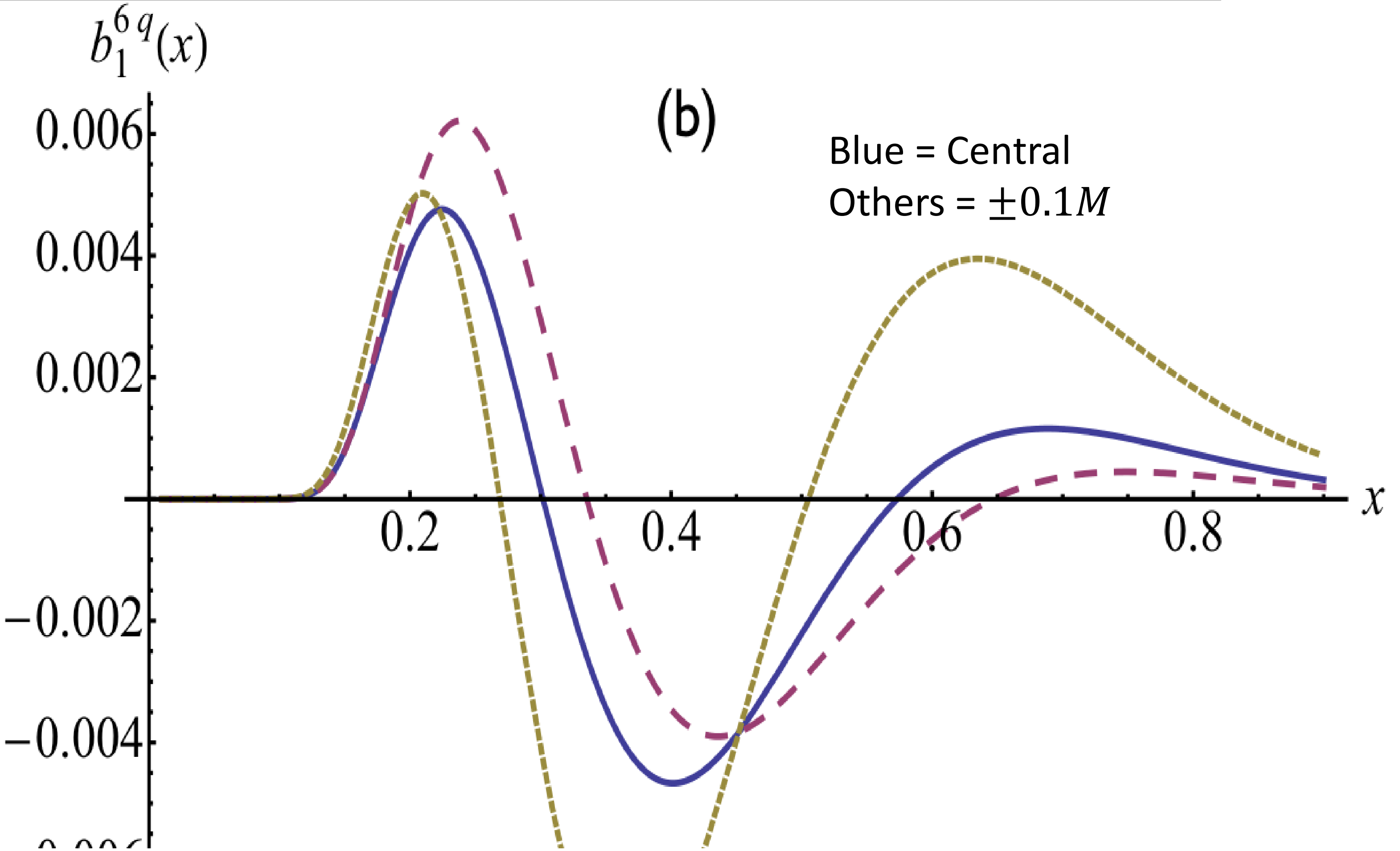
Probability of Hidden-Color Effects

- Even though experimental upper limit of $P_{6q} < 1.5\%$, a much smaller value (0.15%) can have a significant effect on b_1

G Miller, PRC **89** 045203 (2014)

6-Quark, Hidden Color

- 6-quark, hidden color states predict large negative b_1 at large x
- Using central values R=1.2 fm, m=338 MeV

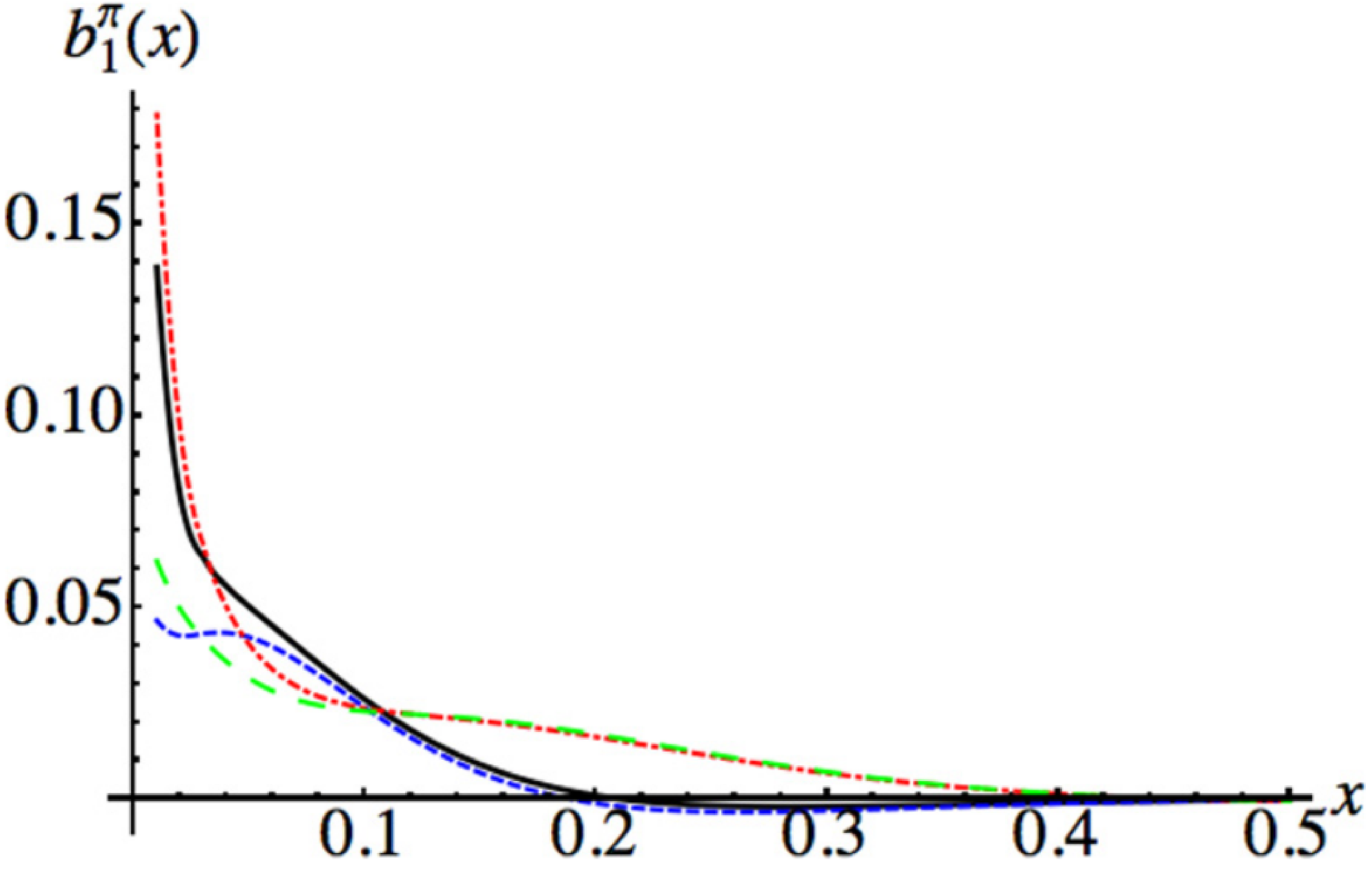


G Miller, PRC **89** 045203 (2014)

6-Quark, Hidden Color

- Pionic effects alone would violate Close-Kumano Sum Rule

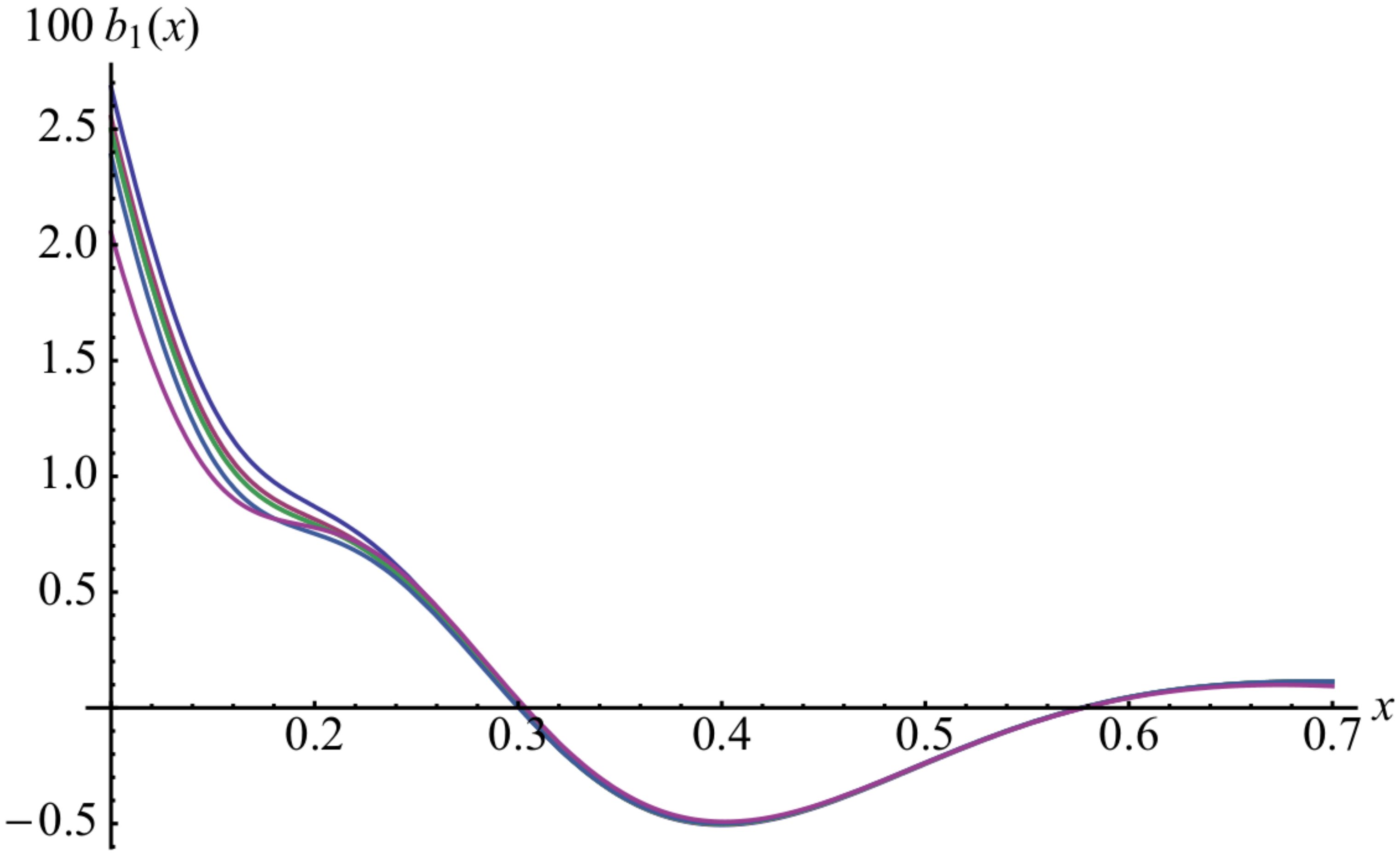
$$\int b_1(x)dx = 0$$



G Miller, PRC **89** 045203 (2014)

6-Quark, Hidden Color

- First complete theory to reproduce anomalous HERMES result
- $b_1^{\pi} + b_1^{6q}$ predictions made for upcoming JLab b_1 measurement



G Miller, PRC **89** 045203 (2014)

Orbital Angular Momentum and GPDs

Deuteron angular momentum dominated by the GPD H

- $J_q = \frac{1}{2}\int dx x H_2^q(x, 0{,}0)$
  - (Future tensor-polarized DVCS experiment (A_{UT}) would be ideal test)
- Sum rule can calculate normal nuclear effects with high precision, giving $H_2 \approx H + E$
- Any measured deviation sheds light on elusive gluon angular momentum

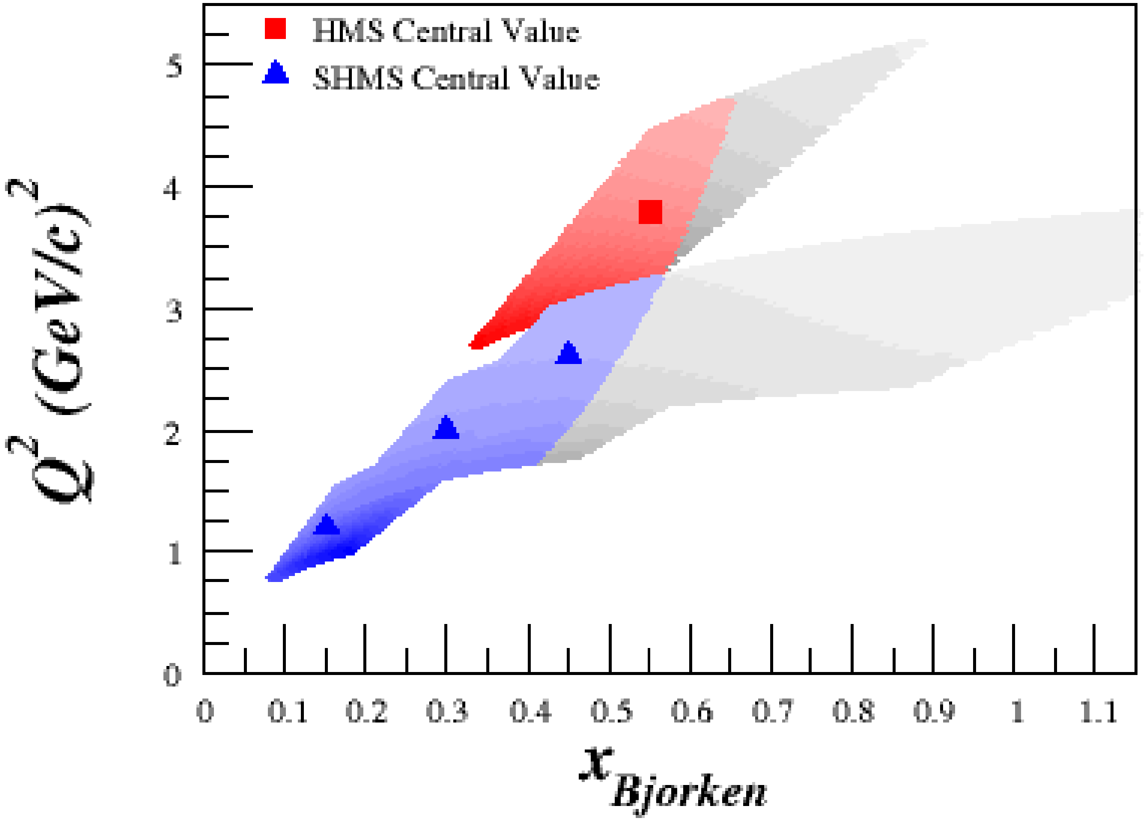
Important for Spin Crisis!

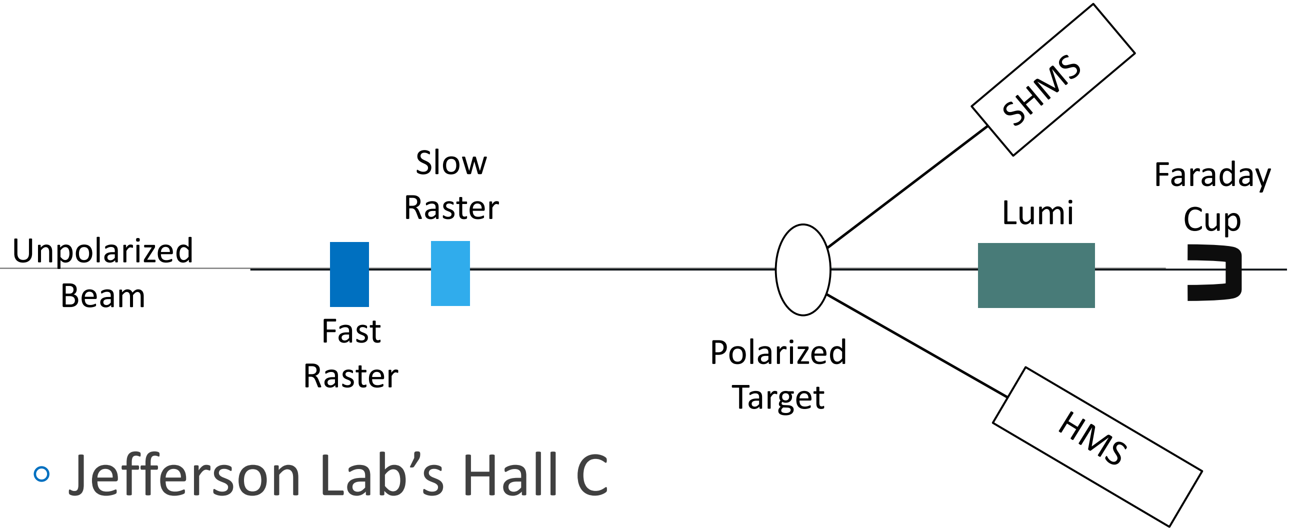
$b_1 = H_5(x, 0{,}0)$ needed to test assumptions in sum rule[1]

- Relates to gravitomagnetic form factors[2]
- $\int dx x H_5(x, \xi, t) = -\frac{t}{8M_D^2}\mathcal{G}_6(t) + \frac{1}{2}\mathcal{G}_7(t)$

[1] SK Taneja, *et al*, PRD **86** 036008 (2012)
[2] OV Teryaev, Front.Phys. **11** 111027 (2016)

b_1 Kinematics





- Jefferson Lab's Hall C
- Unpolarized beam, tensor polarized target (longitudinal alignment)
- Identical equipment to A_{zz}

Det.	x	Q^2 (GeV^2)	W (GeV)	$E_{e'}$ (GeV)	$\theta_{e'}$ (deg)	Rate (kHz)	Time (Day)
SHMS	0.15	1.21	2.78	6.70	7.4	1.66	6
SHMS	0.30	2.00	2.36	7.45	9.0	0.79	9
SHMS	0.45	2.58	2.0	7.96	9.9	0.38	15
HMS	0.55	3.81	2.0	7.31	12.5	0.11	30

Tensor Structure Function, b_1

Measure anomalous HERMES point with much higher precision & tighter Q^2 range

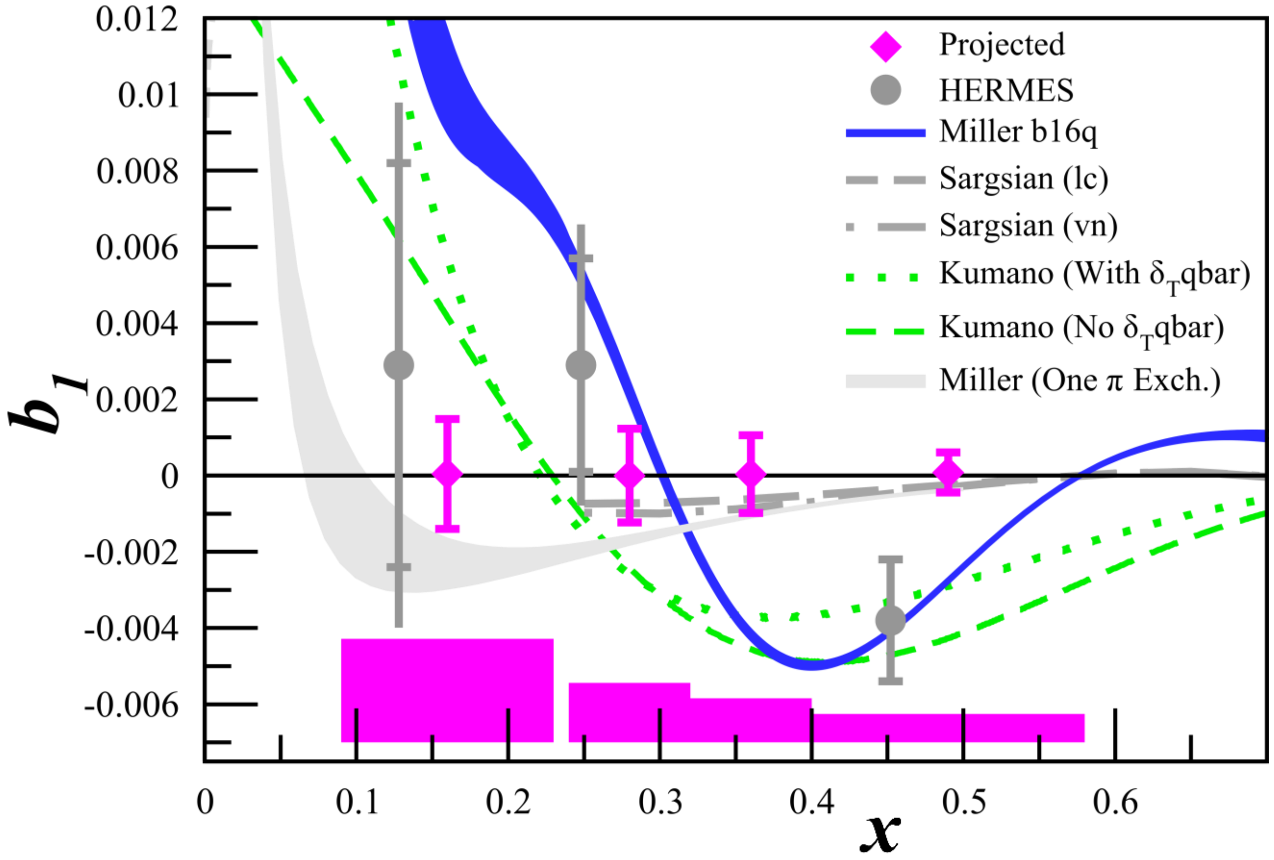
Map out zero-crossing

Gain insight into:

- Close-Kumano sum rule[1]
- 6-quark hidden color[2]
- OAM and spin crisis[3]
- Pionic effects[2,4]
- Polarized sea quarks[4]

Approved JLab Experiment C12-13-011

- Spokespersons: K. Slifer, E. Long, D. Keller, P. Solvignon, J.P. Chen, O.R. Aramayo, N. Kalantarians



[1] FE Close, S Kumano, Phys. Rev. **D42,** 2377 (1990)
[2] G Miller, Phys. Rev. **C89,** 045203 (2014)
[3] SK Taneja *et al*, Phys. Rev. **D86,** 036008 (2012)
[4] S Kumano, Phys. Rev. **D82,** 017501 (2010)

Δ (or b_4)

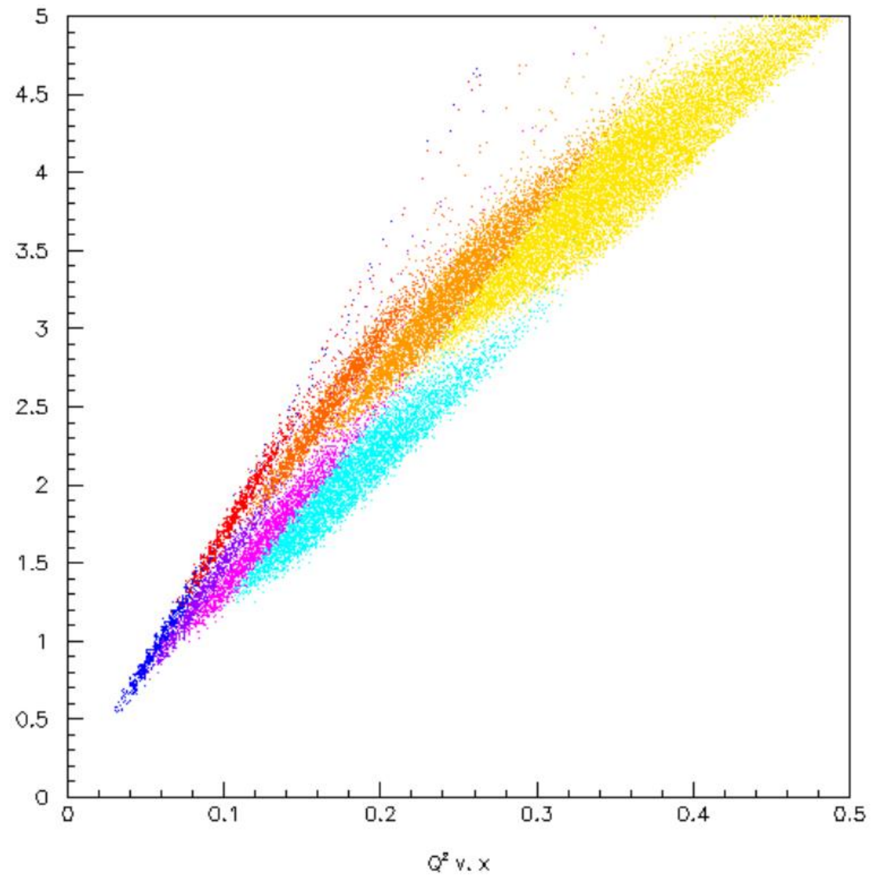
LOI12-16-006: Search for Exotic Gluonic States in the Nucleus

Authors:

J. Maxwell*, W. Detmold, R. Jaffe, R. Milner, D. Crabb, D. Day, D. Keller, O.A. Rondon, M. Jones, C. Keith, J. Pierce

Tensor Structure Function, b_4 (or Δ)

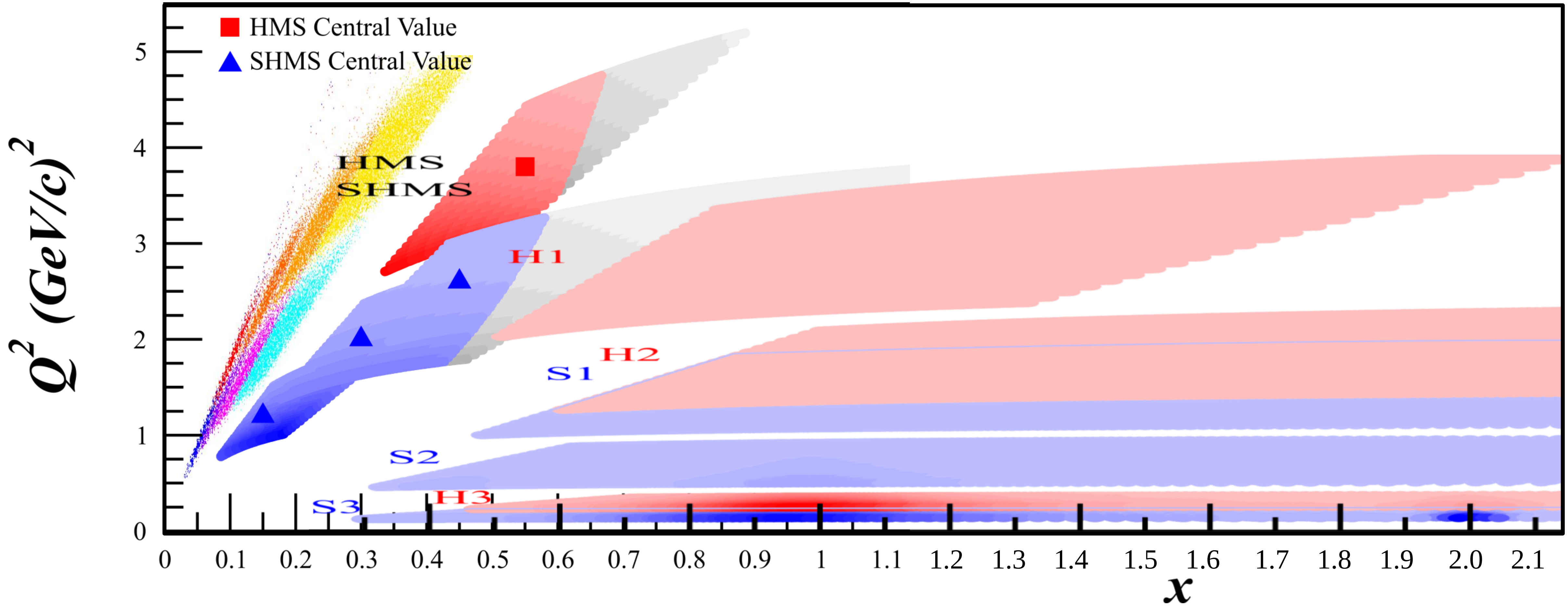
- Hadronic double helicity flip structure function, $\Delta(x, Q^2) = b_4$
- Unpolarized beam on transversely-aligned target
- Insensitive to bound nucleons or pions
- Any non-zero value indicates exotic gluonic components
- New lattice QCD result for first moment of Δ(x, Q2) in a ϕ meson is preliminary, but very promising (arXiv:1606.04505)
- Encouraged for full proposal submission, updated LOI submitted



J. Maxwell, *et al*, JLab LOI-14-001

R Jaffe, A Manohar, Phys. Lett. B **223,**218 (1989)

JLab Tensor Program (So far...)



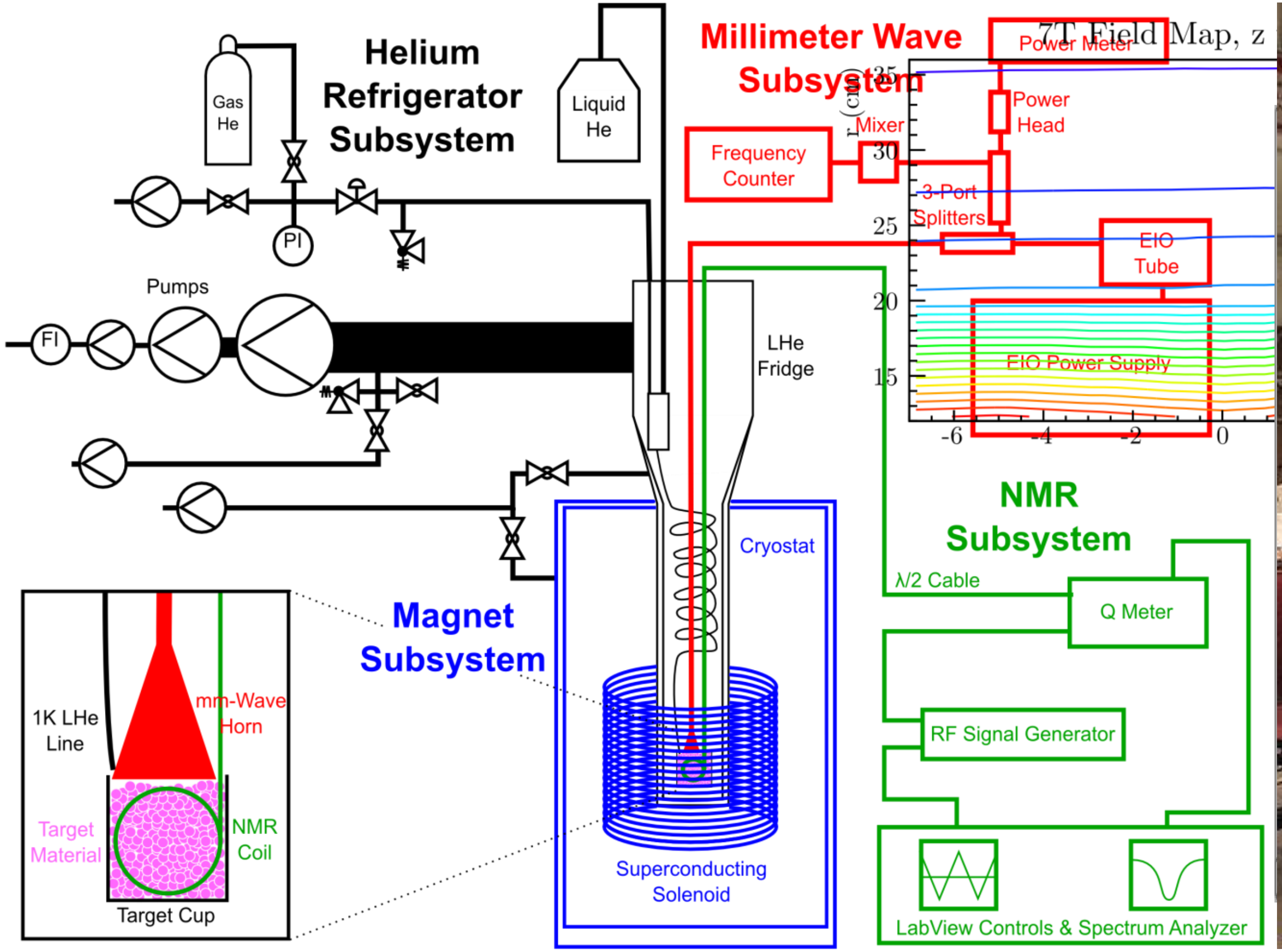
Tensor Polarized Target

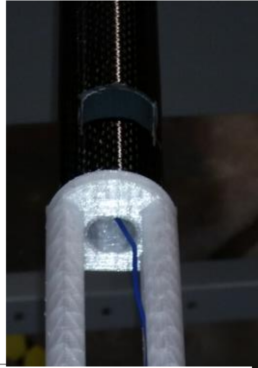
Tensor Polarization Techniques

- **Unpolarized Target + Polarimeter**
  - D_2O waterfall[1]
  - Liquid D_2[2]
  - Medium-high luminosity, no polarization enhancement
- **Gas Jet/Storage Cell Target**[3]
  - Low luminosity, very high tensor polarization
- **Solid Polarized DNP Target**[4]
  - High luminosity, polarization enhancement, large dilution at high x

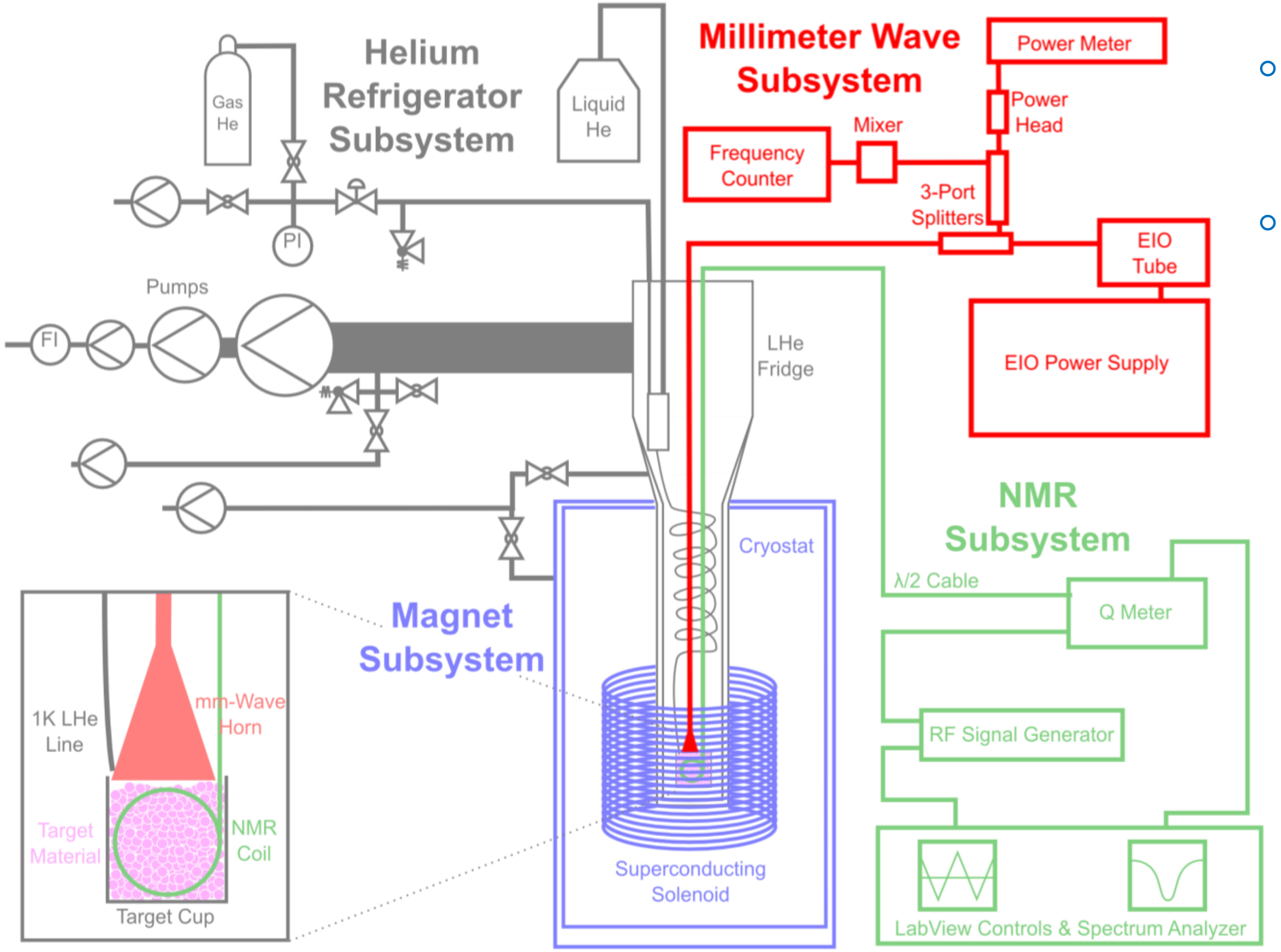
[1] ME Schulze, *et al*, PRL **52** 597 (1984)
[2] D Abbot, *et al*, PRL **84** 5053 (2000)
[3] AV Evstugneev, *et al*, NIM A **238** 12 (1985)
[4] B Boden, *et al*, Z. Phys. C **49** 175 (1991)

Dynamic Nuclear Polarization (DNP)



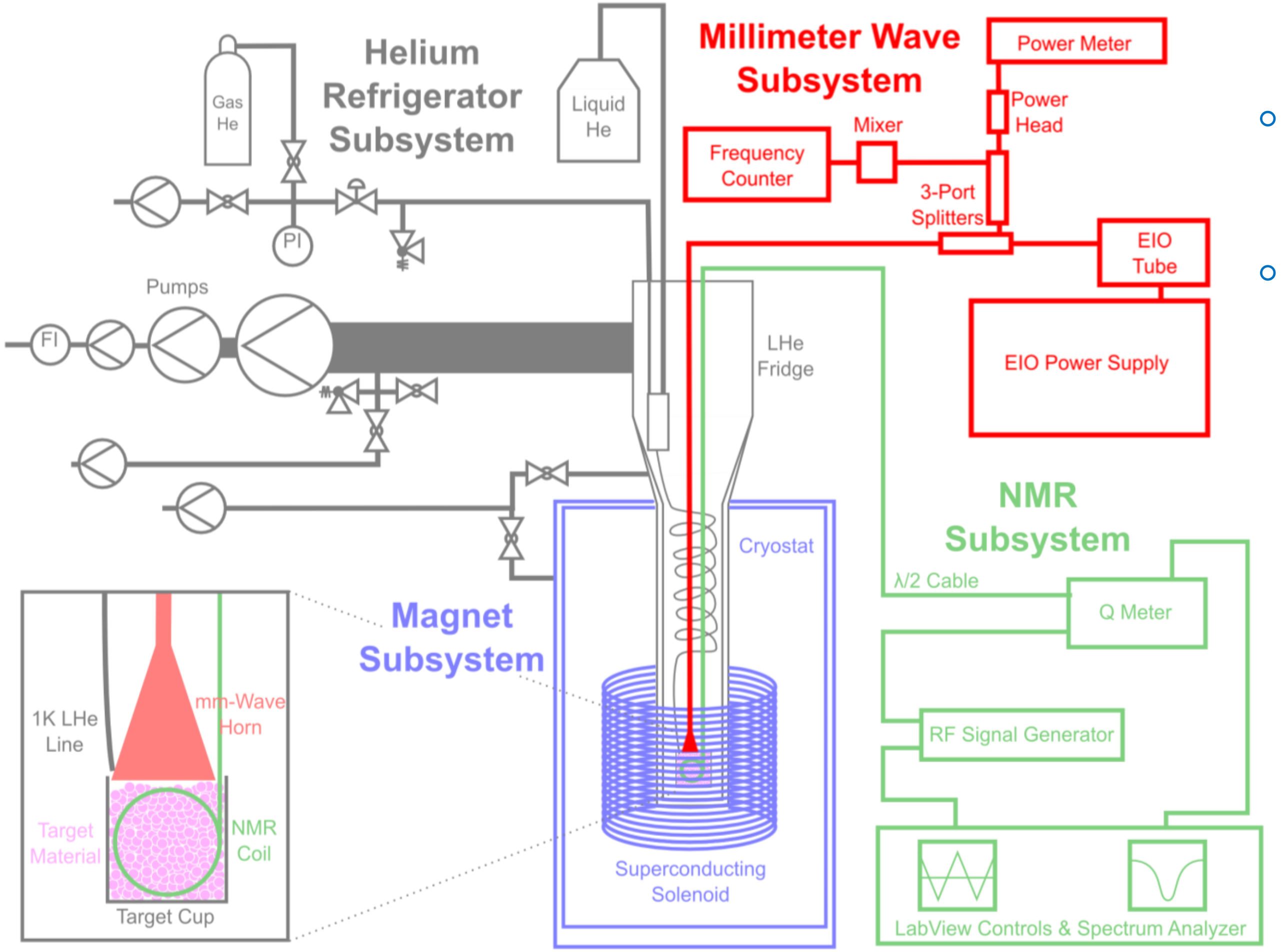


Dynamic Nuclear Polarization (DNP)



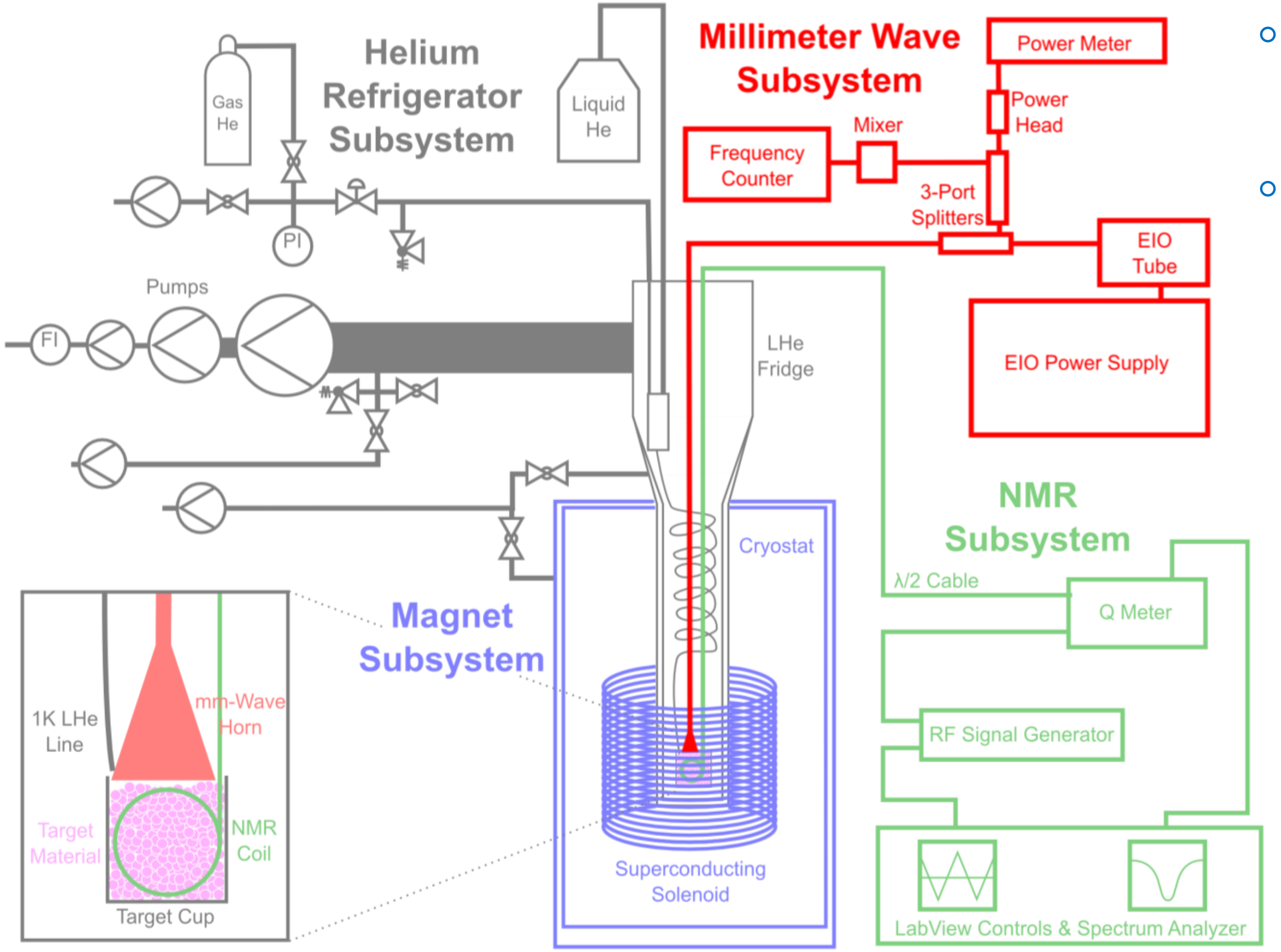
- Traditionally, Nucl. Phys. Uses EIO tubes & rectangular waveguides (WR) for mmWave
- Rectangular Waveguide Disadvantages:
  - Transmit only fundamental frequency
    - One frequency range = One $\boldsymbol{B}$-field (± ~1 T)
  - High loss (~8 dB/m)
    - Very significant with EIO, as EIO affected by fringe fields and must be ~few meters away from target
      - 20 W EIO → 0.01 W on target from losses (pre-horn)
  - Conductive metal from source to horn
    - → Higher heat transfer
      - → Wasted LHe

Dynamic Nuclear Polarization (DNP)



- Replace rectangular with corrugated waveguides
- Corrugated Waveguide Advantages:
  - Over modal, 2+ frequency ranges / set
  - Extremely low loss (~0.01 dB/m)
    - Same power on target w/ far lower power mmW source
      - 0.5 W source → 0.498 W on target (pre-horn)
  - Can put gaps ($\approx d$) in guides with minimal loss
    - → Nearly zero heat transfer

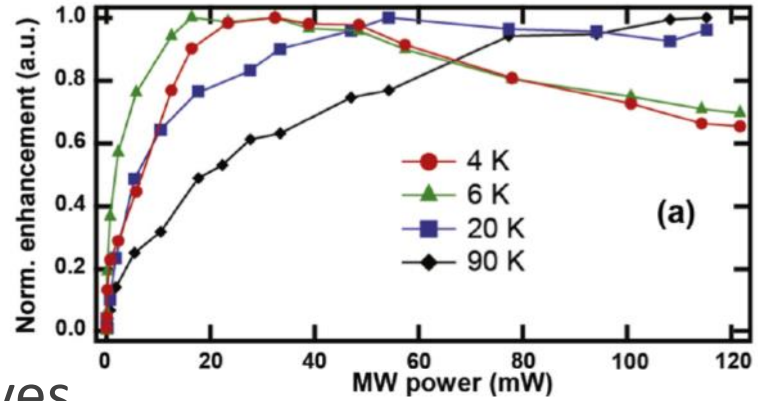
Dynamic Nuclear Polarization (DNP)

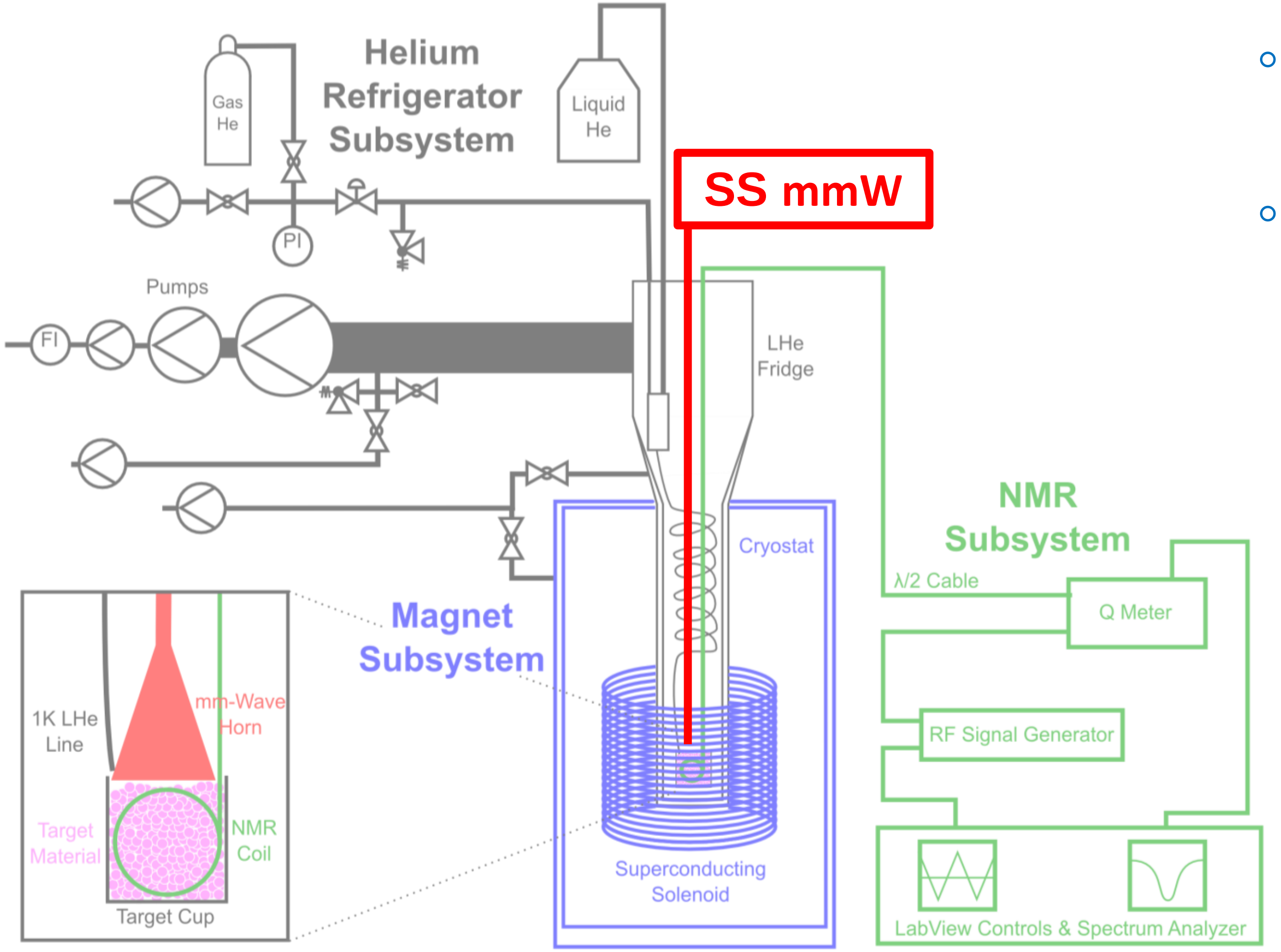


- Traditionally, Nucl. Phys. Uses EIO tubes & rectangular waveguides (WR) for mmWave
- EIO Disadvantages:
  - Need to replace for any significantly higher fields ($$$)
    - $\uparrow \boldsymbol{B} \rightarrow \uparrow P_{zz}$
    - $\uparrow \boldsymbol{B} \rightarrow \uparrow f$
    - $\uparrow \boldsymbol{B} \rightarrow \downarrow P$
    - $\uparrow \boldsymbol{B} \rightarrow \uparrow$ $200k per $\boldsymbol{B}$
  - Affected by fringe fields, must be far from target
    - Requires more waveguides ($)
  - Current UNH DNP mmWave system not complete
  - Limited lifetime ~few thousand hours

Dynamic Nuclear Polarization

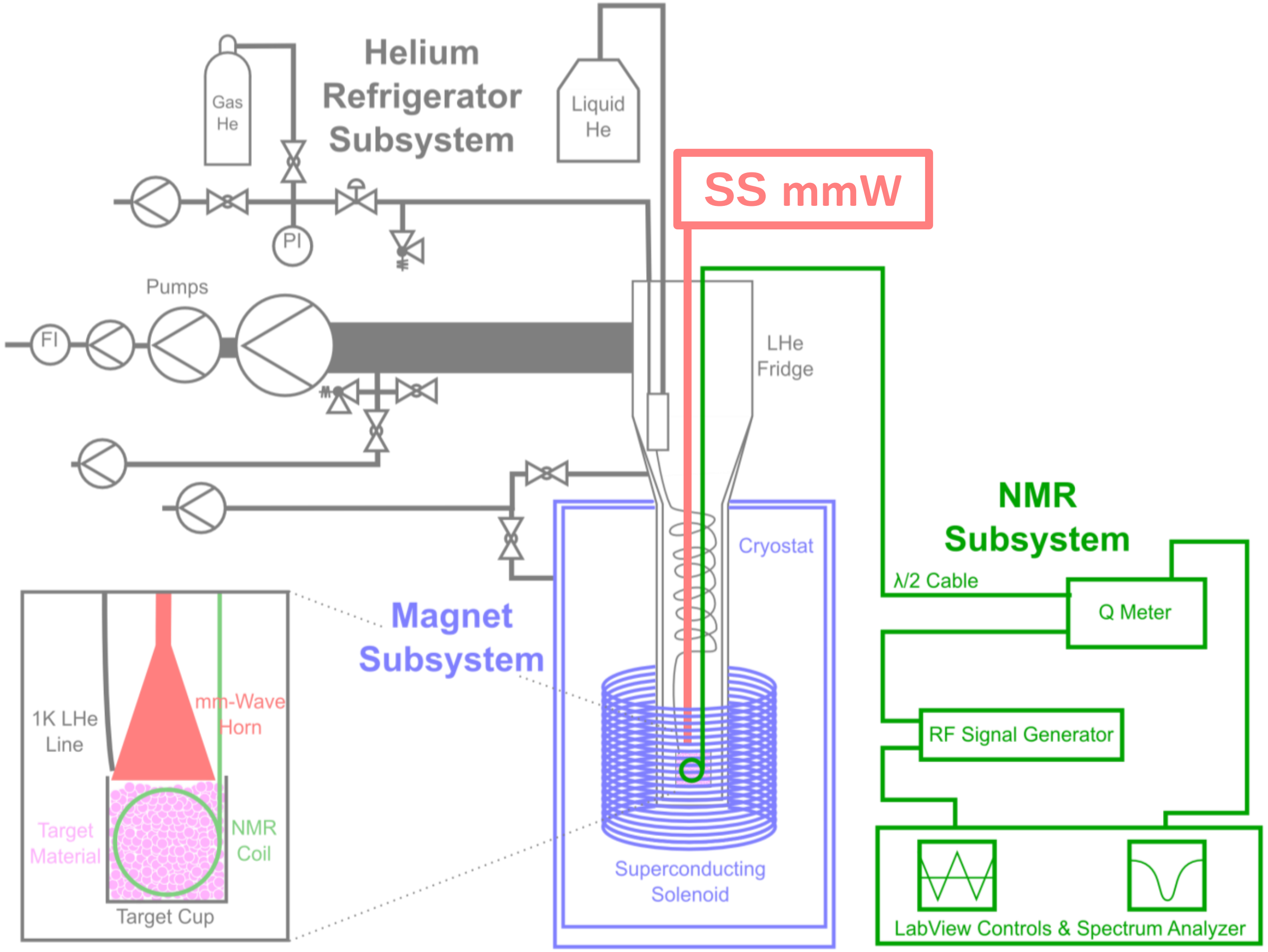
[1]H DNP with SS mmWave
TA Siaw, *et al*, J.Mag.Res. **264** 131 (2016)





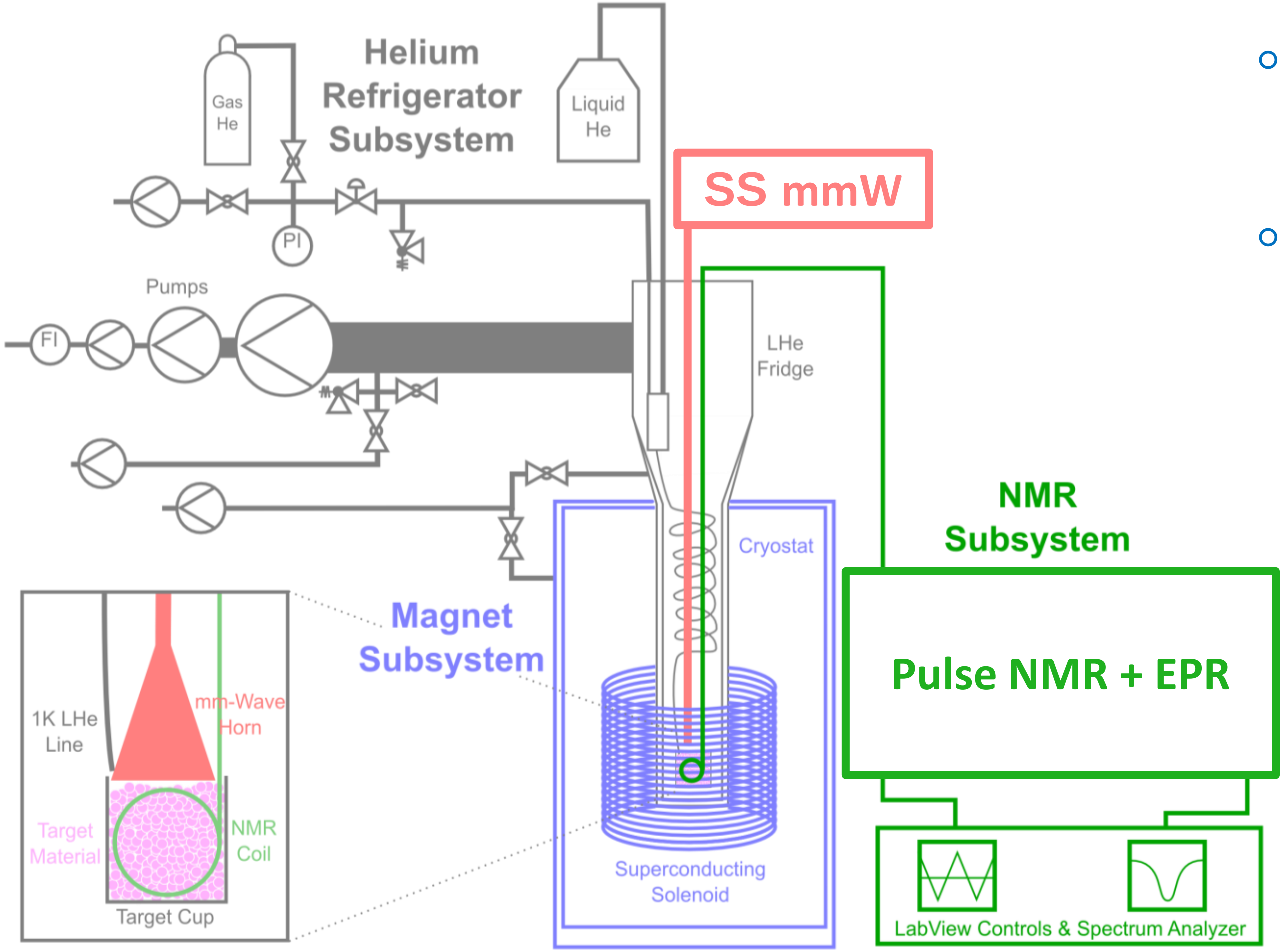
- Replace EIO with Solid State mmWaves
- Advantages:
  - Method established for high-field medical DNP (~10 T)
    - Bring medical DNP back to nuclear physics for P_{zz}!
  - Not affected by magnetic fields
    - Sits close to magnet, reducing losses and costs
  - 3-5x less expensive than EIO set-up
    - Multiple field tests become feasible
  - Can use with frequency doublers and triplers
  - >10x longer lifetime
  - Technology continues advancing rapidly

Dynamic Nuclear Polarization

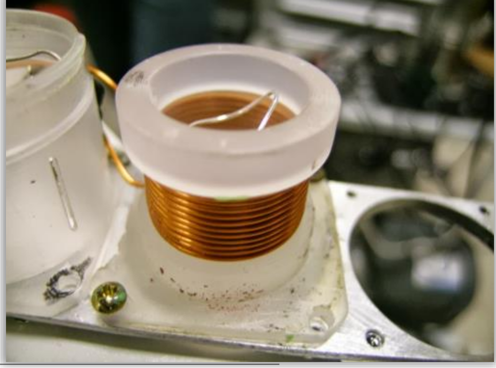


- Traditional Nuclear Physics uses Q Meter for CW NMR
- Disadvantages:
  - Discontinued manufacturing
    - Newest Livermore models from the ‘90s
  - Difficult to tune/repair
  - Slight frequency/field drifts completely ruin calibration
    - Wasted helium from recalibrating
  - Built for an analog age

Dynamic Nuclear Polarization

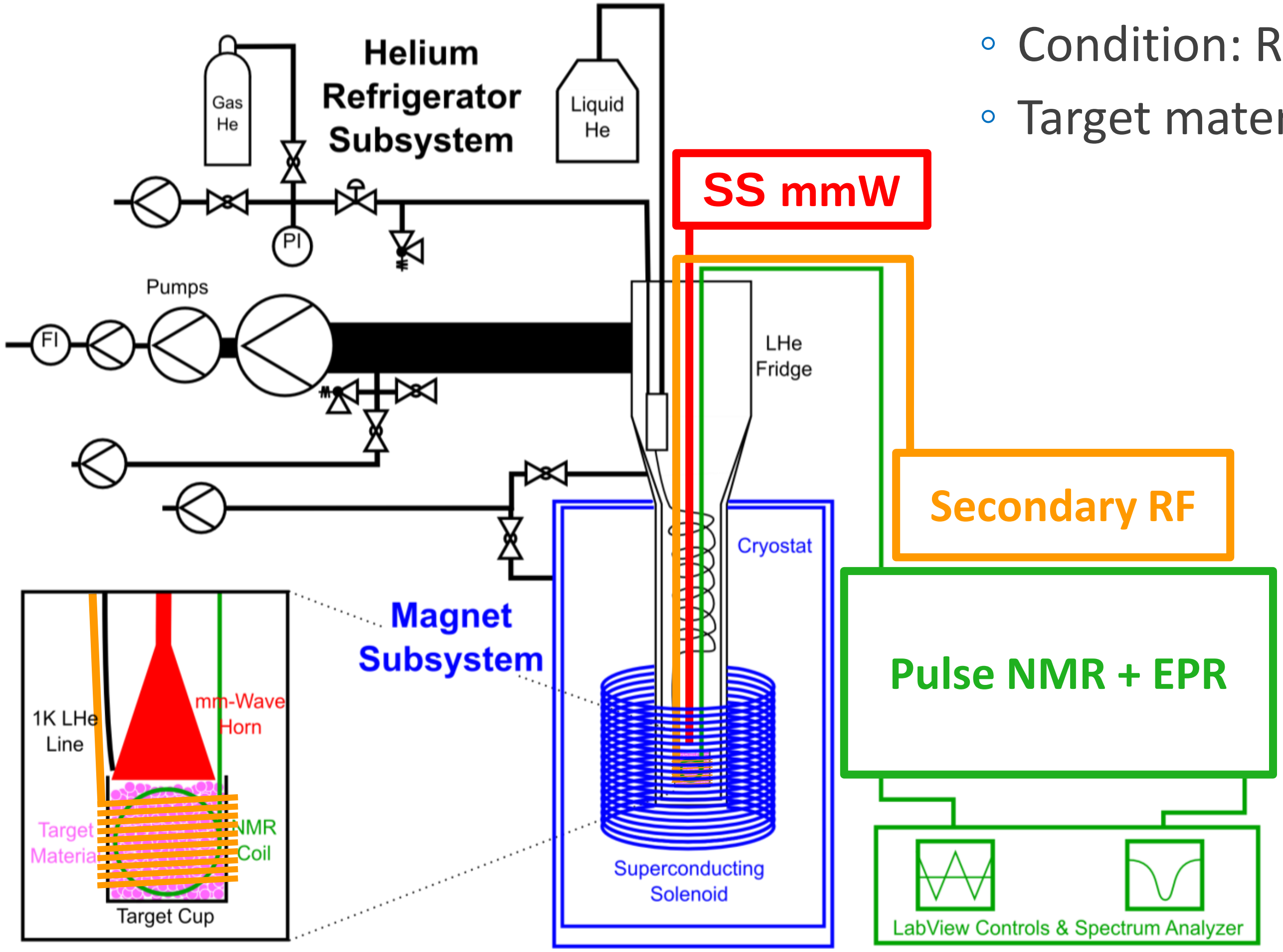


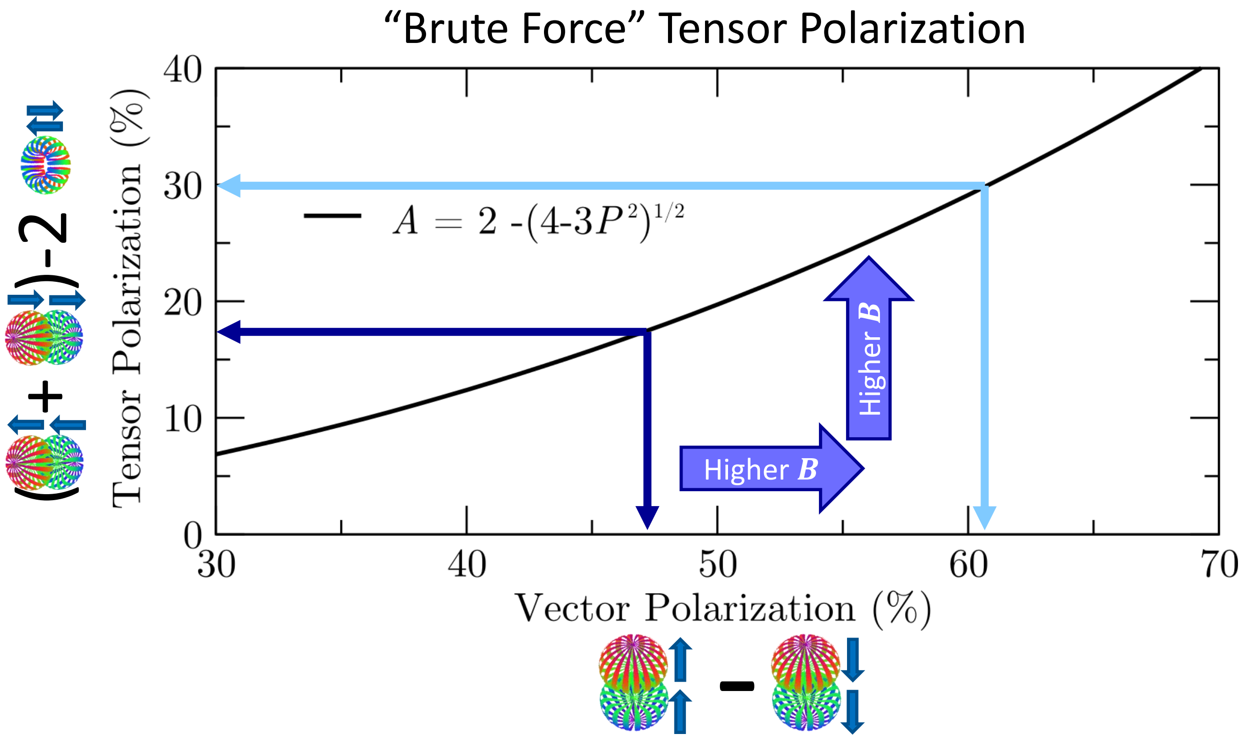
- Replace Q Meter with Pulse NMR + EPR
- Advantages:
  - Proven technology in medical DNP
  - EPR calibration decreases tuning time
    - Saves liquid helium
  - Actively developed & supported
  - Near off-the-shelf running
  - Built for the digital age
  - More time doing physics, less time struggling with NMR



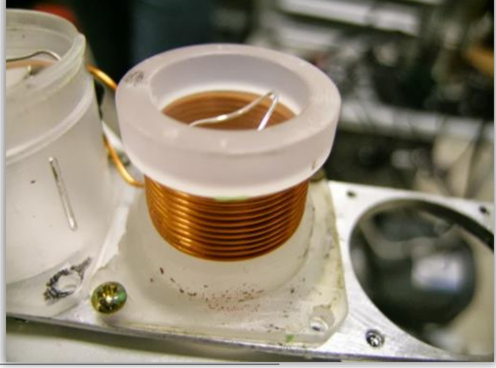
Tensor Polarization with DNP

- Condition: Reach $P_{zz} \sim 30\%$
- Target material: ND_3





Tensor Polarization with DNP



- Condition: Reach $P_{zz} \sim 30\%$
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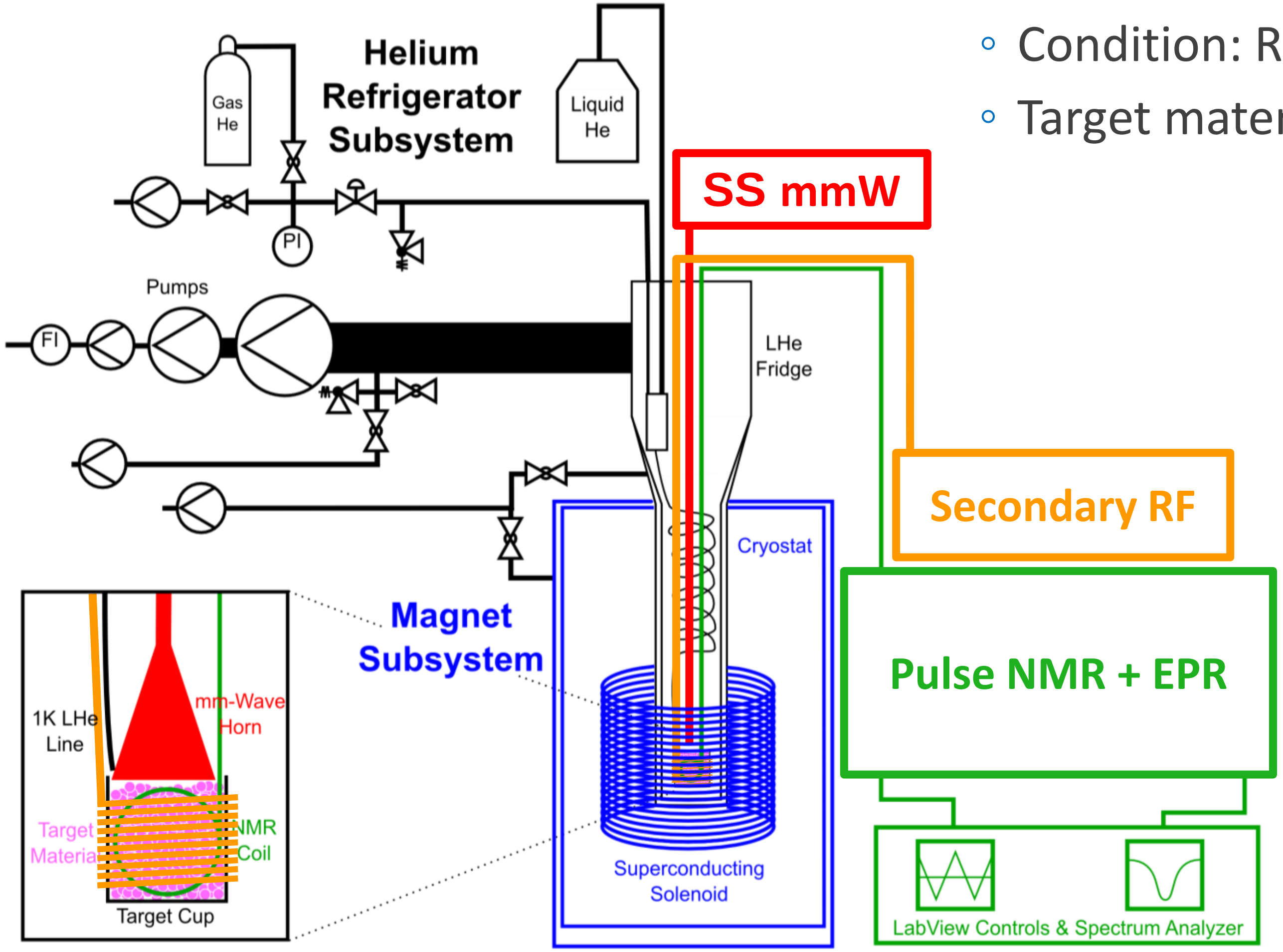
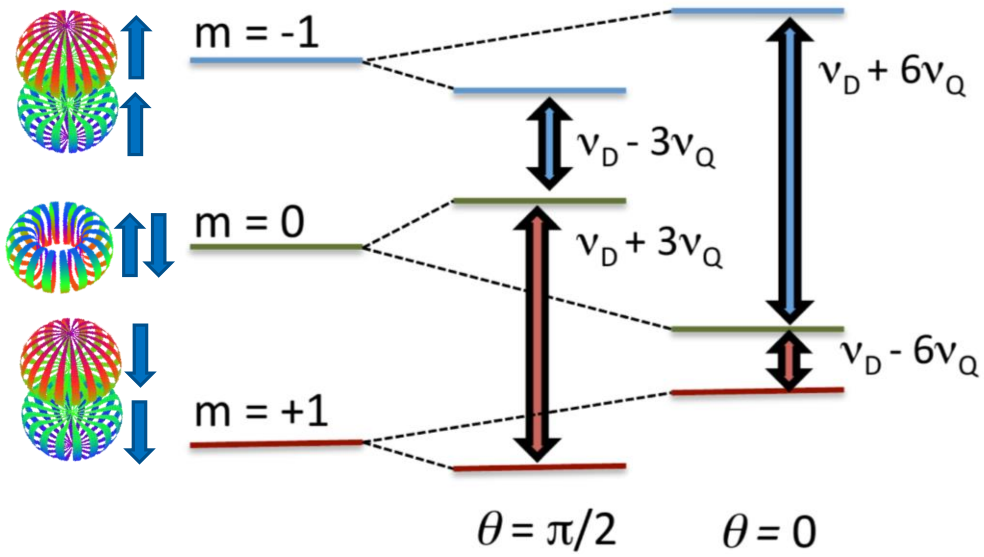
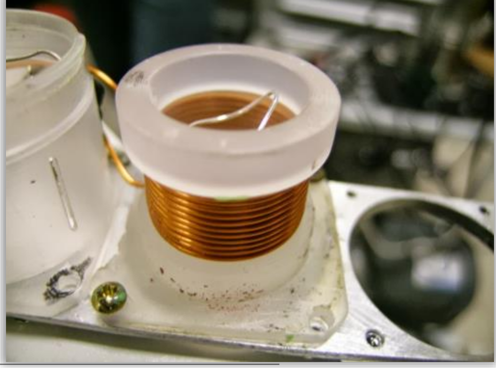
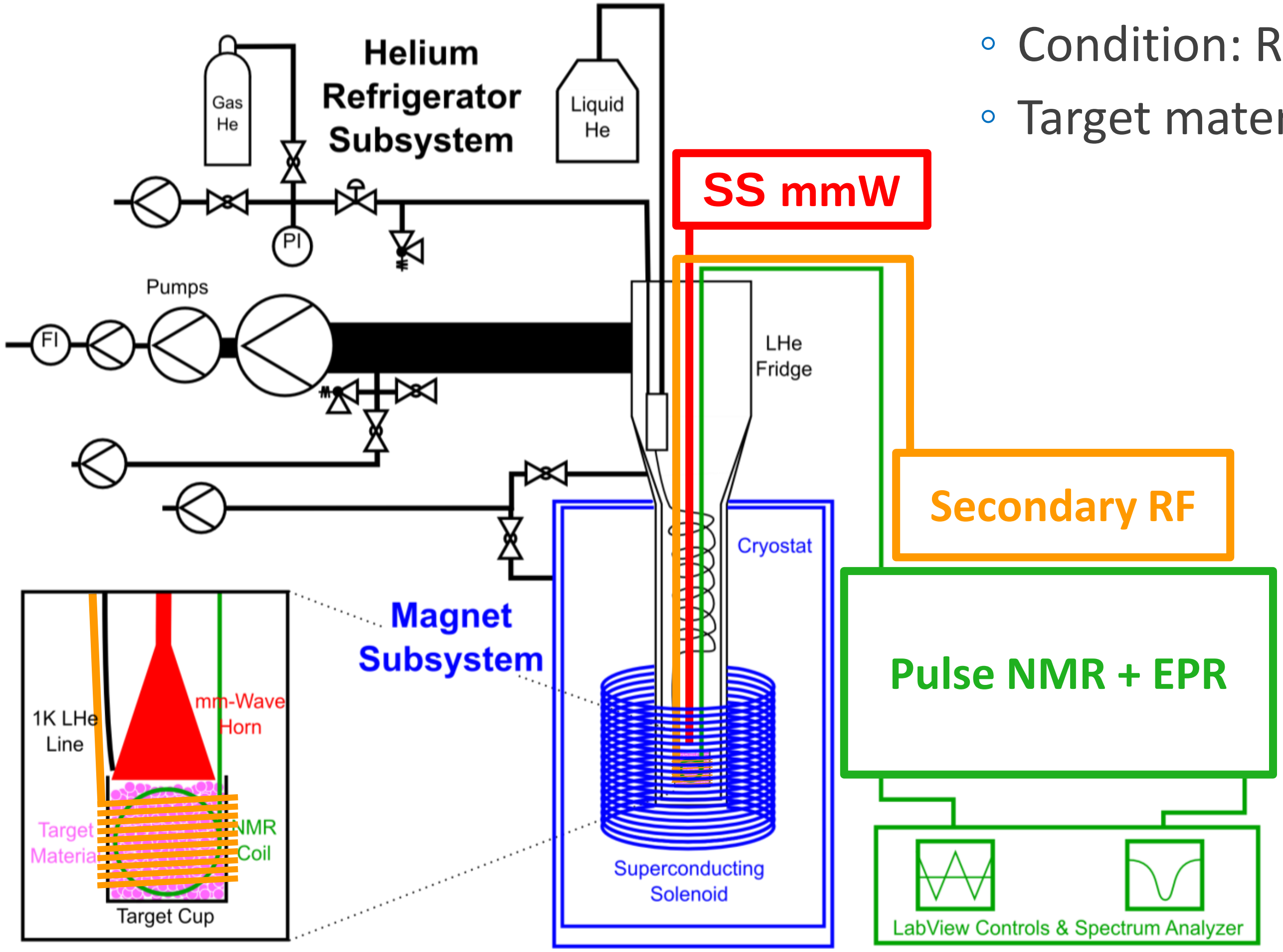




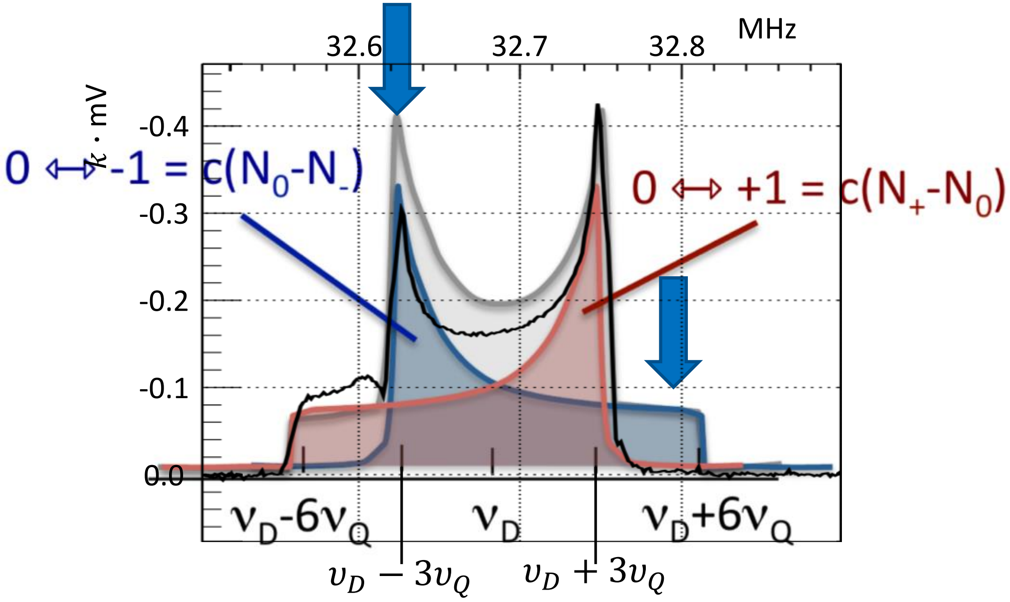
Tensor Polarization with DNP





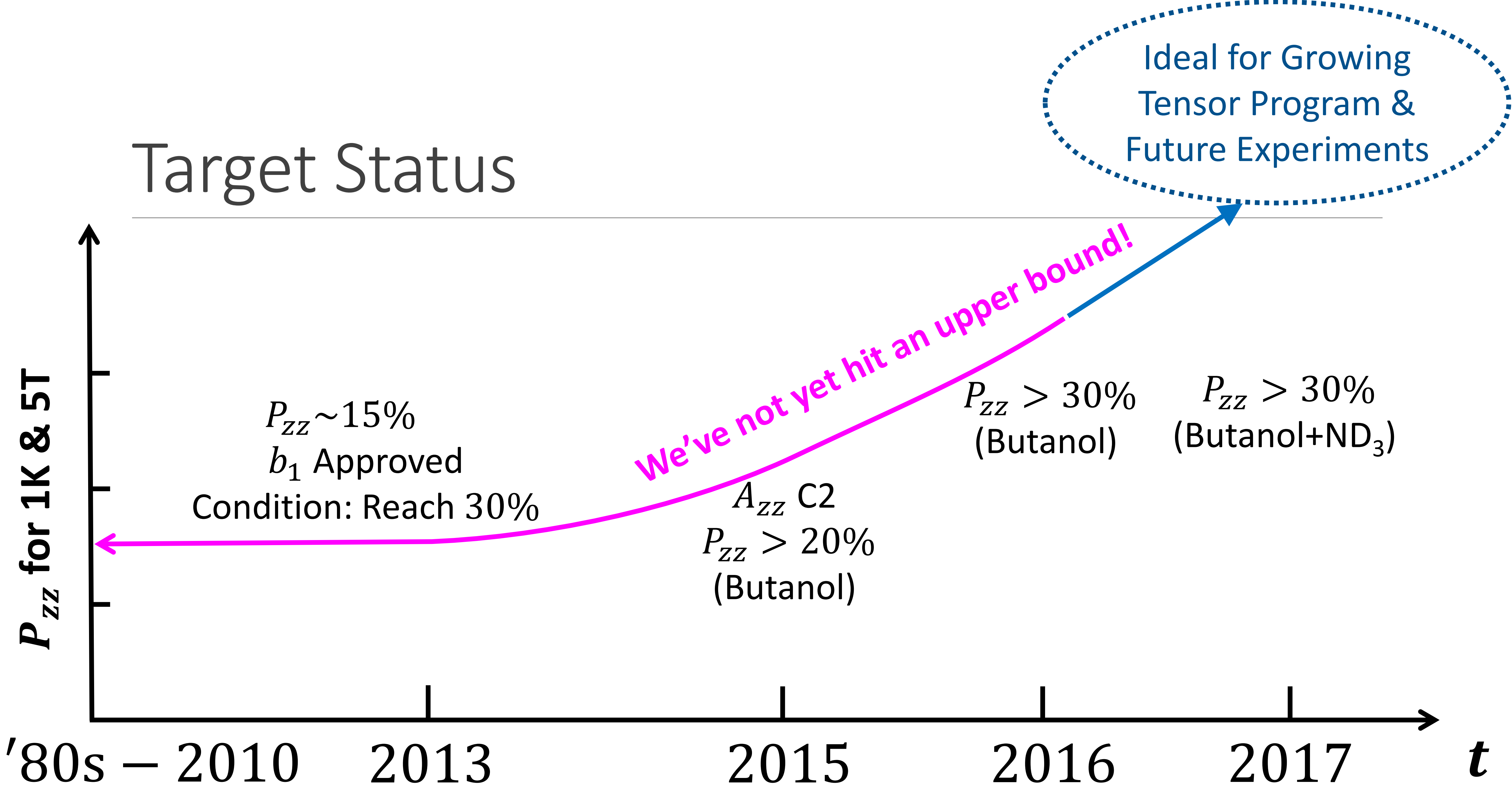
- Condition: Reach $P_{zz} \sim 30\%$
- Target material: ND_3

"Hole Burning" Tensor Enhancement



D Keller, HiX Workshop (2014)
UVA Tensor Enhancement on Butanol (2014)

Target Status



More than 10x less sensitive to systematics than b_1

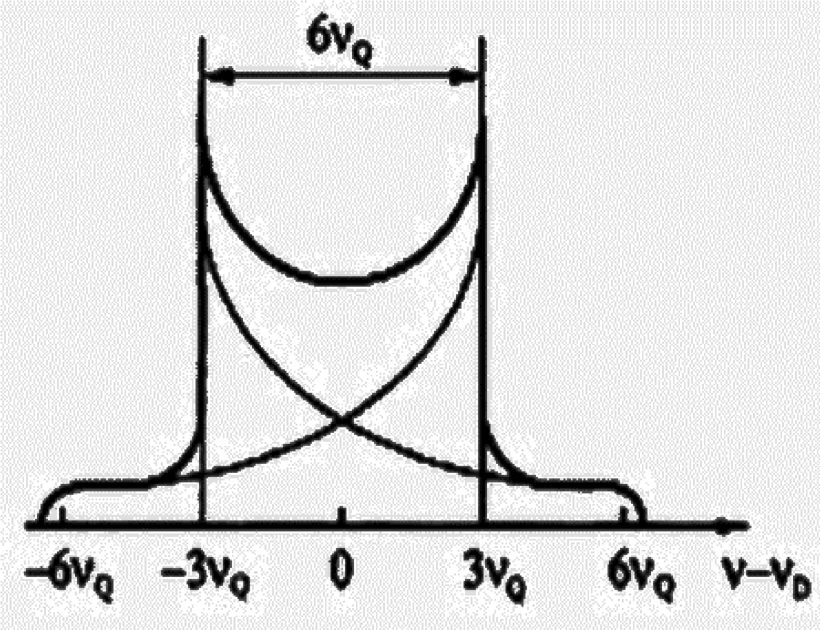
Systematics

Source	A_{zz} Systematic	T_{20} Systematic
Polarization	$3.0-6.0\%$	$3.0-6.0\%$
Dilution factor	6.0%	2.5%
Packing fraction	3.0%	3.0%
Trigger/Tracking Eff.	1.0%	1.0%
Acceptance	0.5%	0.5%
Charge Determination	1.0%	1.0%
Detector resolution and efficiency	1.0%	1.0%
Total	$7.6-9.2\%$	$5.2-7.4\%$

Overhead

Overhead	Number	Time Per (hr)	(hr)
Polarization/depolarization	38	2.0	76.0
Target anneal	15	4.0	60.0
Target T.E. measurement	6	4.0	24.0
Target material change	4	4.0	16.0
Packing Fraction/Dilution runs	20	1.0	20.0
BCM calibration	9	2.0	18.0
Optics	3	4.0	12.0
Linac change	2	8.0	16.0
Momentum/angle change	3	2.0	6.0
			10.3 days

Tensor Polarization Measurement



Vector optimize with microwaves

Fit peaks with convolution

Tensor optimize with RF

Measure change in peaks using Riemann Sum segments

$$P_{zz}^{HB} \approx \frac{A^{NMR}}{A^{I}}\left(P_{zz}^{I} + r_0(P^{I} - P_{zz}^{I})\right)$$

Ratio of instantaneous to initial NMR signal area

Percentage of initial peak shifted any time (from reduced side)

Available tensor enhancement

Rates for D(e,e')X

Assumptions:

$P_{zz} = 30\%$

$p_f = 65\%$

$z_{tgt} = 3$ cm

P.E. Bosted, V. Mamyan, arXiv:1203.2262
M. Sargsian, Private Communication
N. Fomin, et al., Phys. Rev. Lett. 108 (2012) 092502
N. Fomin, et al., Phys. Rev. Lett. 105 (2010) 212502

$$R_{\mathrm{Pol}} = \mathcal{A}\left[\mathcal{L}_{\mathrm{He}}\sigma^{u}_{\mathrm{He}} + \mathcal{L}_{\mathrm{N}}\sigma^{u}_{\mathrm{N}} + \mathcal{L}_{\mathrm{D}}\sigma^{u}_{\mathrm{D}}\left(1+\frac{1}{2}P_{zz}A_{zz}\right)\right]$$

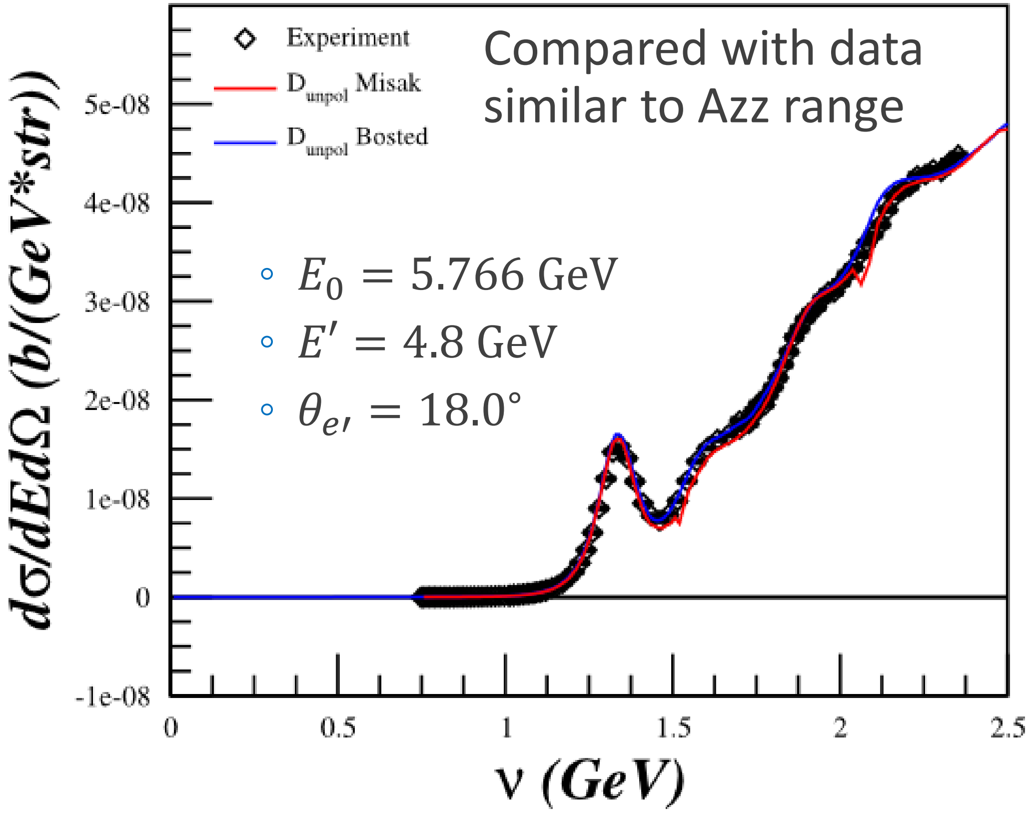
$$R_{\mathrm{Unpol}} = \mathcal{A}[\mathcal{L}_{\mathrm{He}}\sigma^{u}_{\mathrm{He}} + \mathcal{L}_{\mathrm{N}}\sigma^{u}_{\mathrm{N}} + \mathcal{L}_{\mathrm{D}}\sigma^{u}_{\mathrm{D}}]$$

$$N = Rt$$

$$A_{zz} = \frac{2}{f_{dil}P_{zz}}\left(\frac{N_{\mathrm{Pol}}}{N_{\mathrm{Unpol}}} - 1\right)$$

$$\delta A^{\mathrm{stat}}_{zz} = \frac{2}{f_{dil}P_{zz}}\sqrt{\left(\frac{1}{N_{\mathrm{Unpol}}}\sqrt{N_{\mathrm{Pol}}}\right)^2 + \left(\frac{N_{\mathrm{Pol}}}{N^2_{\mathrm{Unpol}}}\sqrt{N_{\mathrm{Unpol}}}\right)^2}$$

- Used combination of P. Bosted and M. Sargsian code to calculate unpolarized cross sections



E. Long, Technical Note, JLAB-TN-13-029

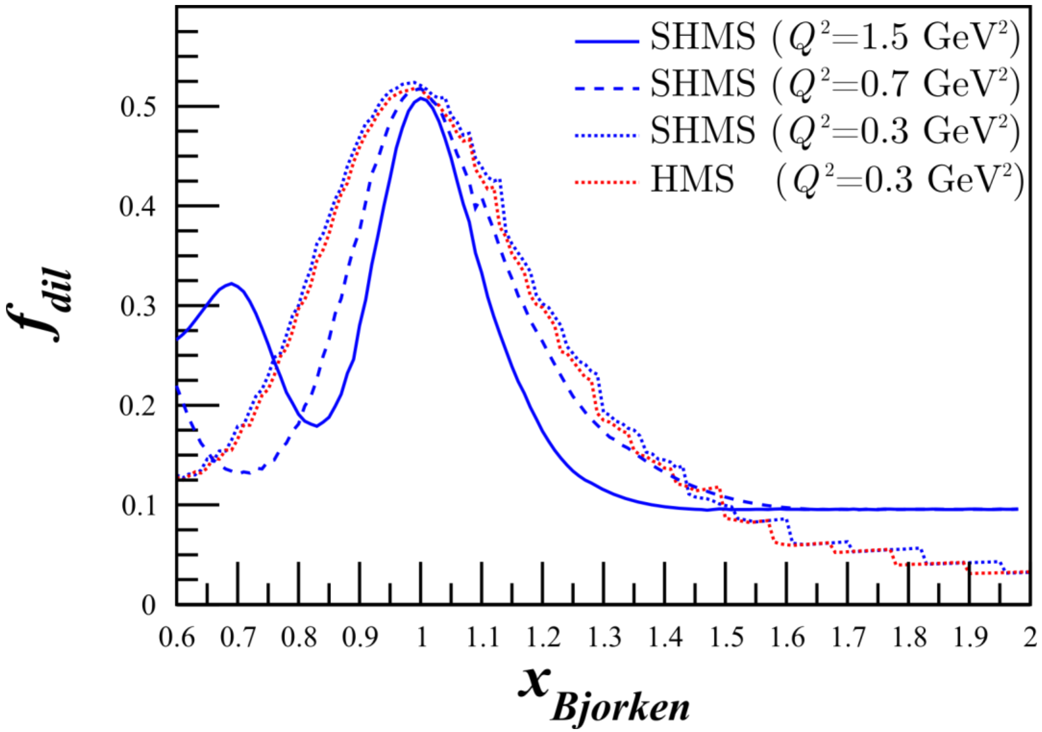
Dilution Factor

"…the background from interaction with nuclei increases as $\alpha(x)$ increases. For example, for a D^{12}C target the ratio of the cross sections σ_A for A=^{12}C and A=D is of the order of 40 for $x \sim 1.3$ and increases with x."

- L.L. Frankfurt, M.I. Strikman, Phys. Rept. **160** (1988) 235

$$f_{dil} = \frac{\mathcal{L}_{\mathrm{D}}\sigma_{\mathrm{D}}}{\mathcal{L}_{\mathrm{N}}\sigma_{\mathrm{N}} + \mathcal{L}_{\mathrm{He}}\sigma_{\mathrm{He}} + \mathcal{L}_{\mathrm{D}}\sigma_{\mathrm{D}} + \sum \mathcal{L}_{\mathrm{A}}\sigma_{\mathrm{A}}}$$

With the 12 GeV upgrade and the new SHMS, this measurement becomes possible even with the low dilution factor at high x



Elastic Tensor Observables

Table 4. World data for tensor polarization observables.

Experiment	Type	Q (GeV)	Observables	Number of points	Year and reference
Bates	Polarimeter	0.34, 0.40	t_{20}	2	1984 [56]
Novosibirsk VEPP-2	Atomic beam	0.17, 0.23	T_{20}	2	1985 [57, 58]
Novosibirsk VEPP-3	Storage cell	0.49, 0.58	T_{20}	2	1990 [59]
Bonn	Polarized target	0.71	T_{20}	1	1991 [60]
Bates	Polarimeter	0.75–0.91	t_{20}, t_{21}, t_{22}	3	1991 [61, 62]
Novosibirsk VEPP-3	Storage cell	0.71	T_{20}	1	1994 [63]
NIKHEF	Storage cell	0.31	T_{20}, T_{22}	1	1996 [64]
NIKHEF	Storage cell	0.40–0.55	T_{20}	3	1999 [65]
JLab Hall C 94-018	Polarimeter	0.81–1.31	t_{20}, t_{21}, t_{22}	6	2000 [4]
Novosibirsk VEPP-3	Storage cell	0.63–0.77	T_{20}	5	2001 [66]
VEPP-3	Internal gas	1.65-4.26	T_{20}, T_{21}	6	2003
Bates	Internal gas	0.42-0.89	T_{20}, T_{21}	9	2011

R Gilman, F Gross, J. Phys. G **28** R37 (2002)

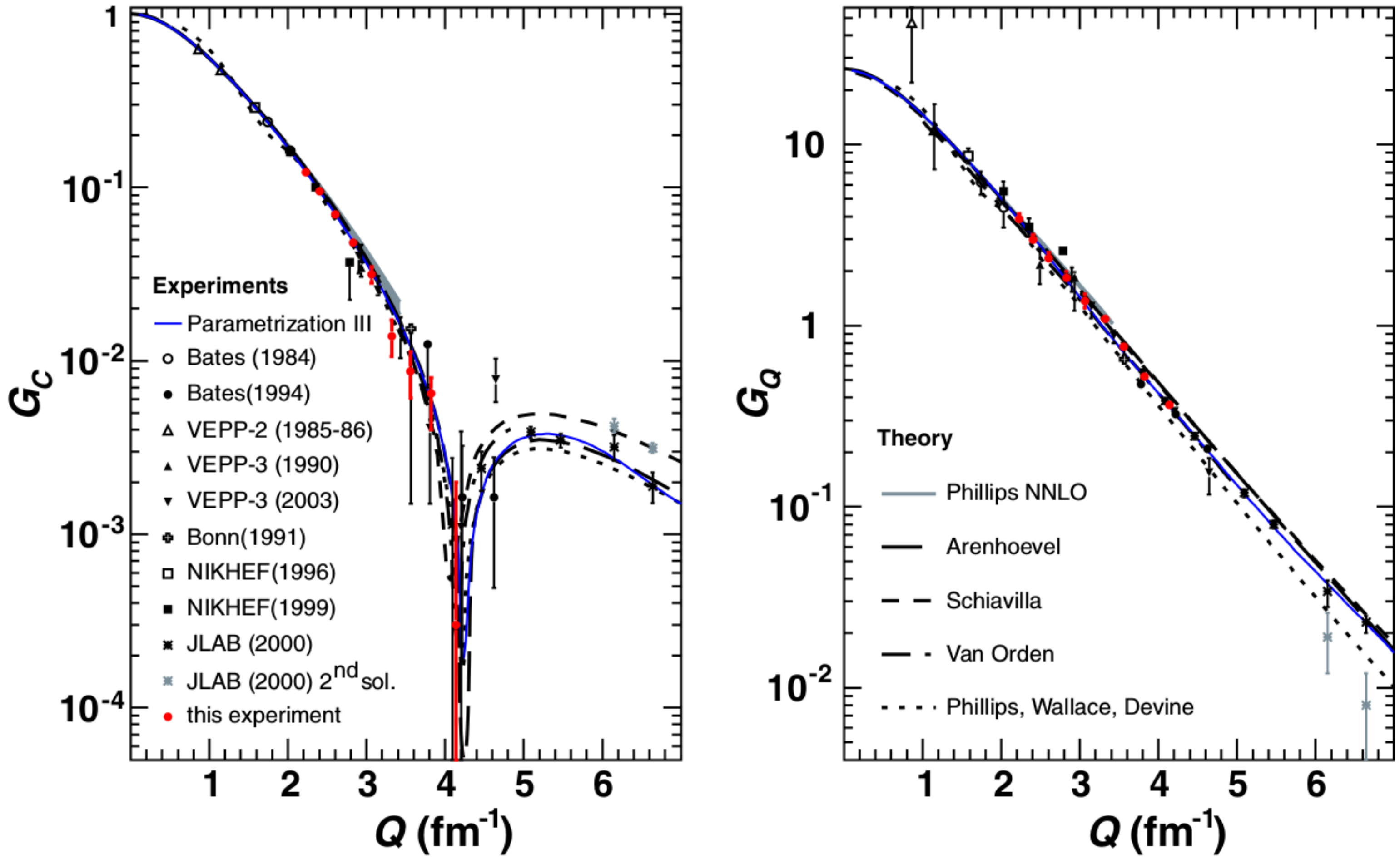
Elastic Tensor Observables

$Q = 7\ \mathrm{fm}^{-1} \rightarrow Q^2 = 1.9\ \mathrm{GeV}^2$

$$A = G_C^2 + \frac{2}{3}\eta G_M^2 + \frac{8}{9}\eta^2 G_Q^2$$

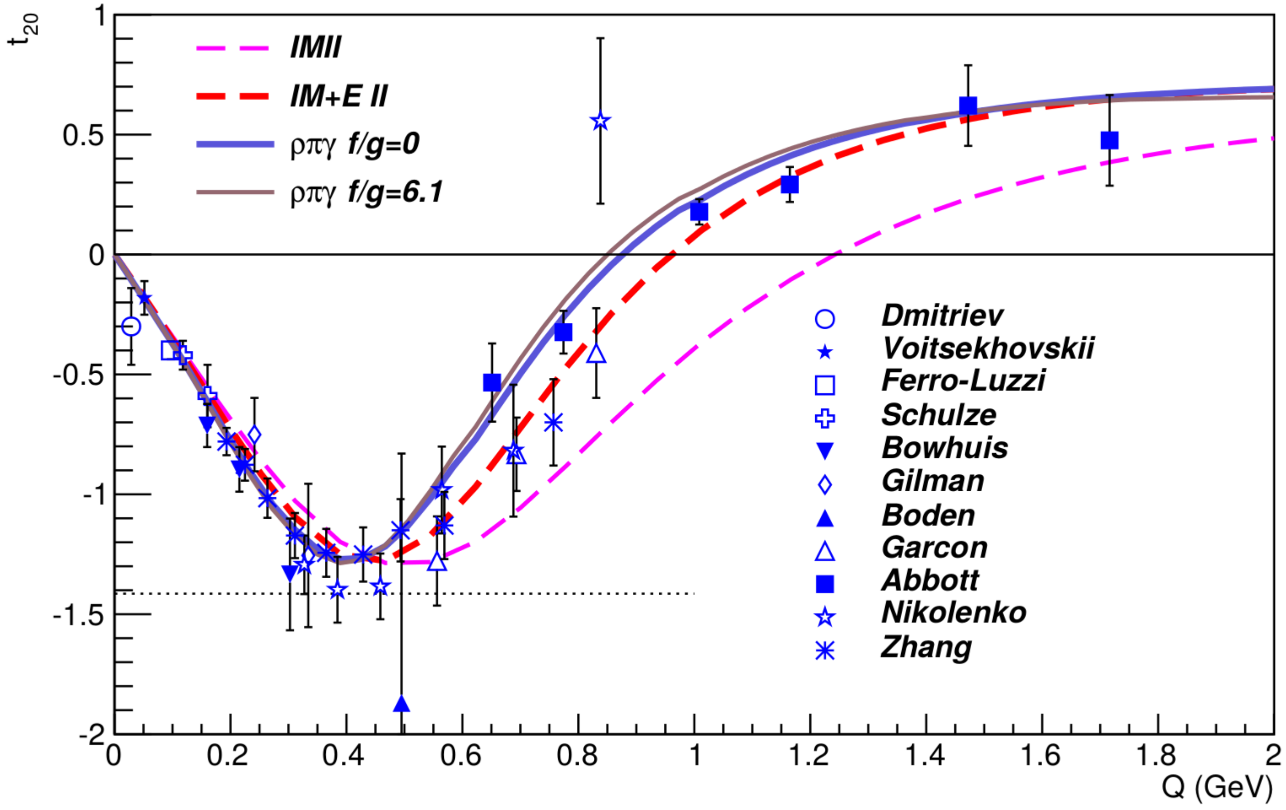
$$B = \frac{4}{3}\eta(1+\eta)G_M^2$$

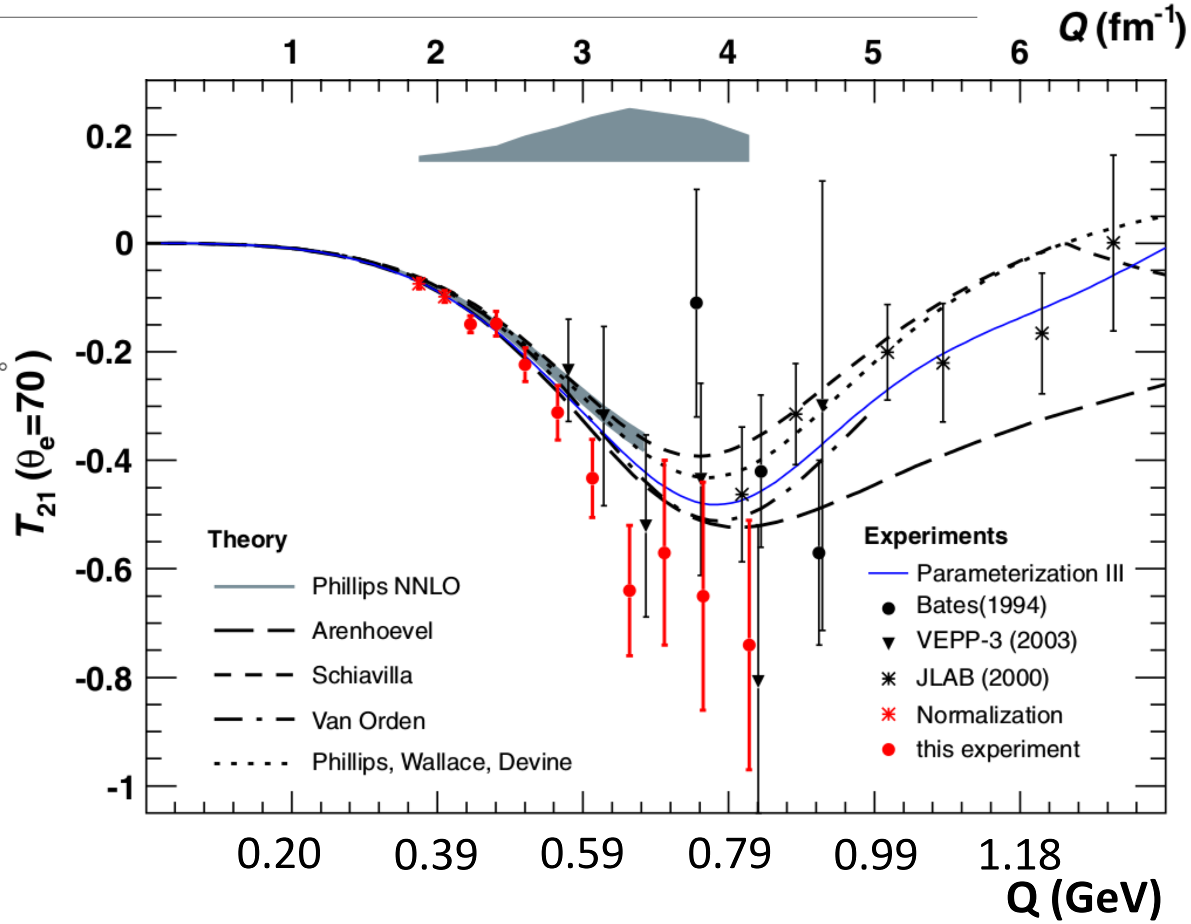
$$T_{20} = -\frac{\frac{8}{9}\eta^2 G_C^2 + \frac{8}{3}\eta G_C G_Q}{\sqrt{2}\left[A + B\tan^2\left(\frac{\theta}{2}\right)\right]} + \frac{\frac{2}{3}\eta G_M^2\left[\frac{1}{2} + (1+\eta)\tan^2(\theta/2)\right]}{\sqrt{2}\left[A + B\tan^2\left(\frac{\theta}{2}\right)\right]}$$



RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)

Elastic Tensor Observables





RJ Holt, R Gilman, Rep. Prog. Phys. **75** 086301 (2012)

C Zhang, *et al*, PRL **107** 252501 (2011)

Diluting Asymmetries

With an unpolarized beam and a longitudinally polarized target,

- $h = 0$
- $\phi_d = 0$
- $\sin \phi_d = 0$

$$\sigma(h,\, P_1^d,\, P_2^d) = \sigma_0[1 + P_1^d \alpha_d^V + P_2^d \alpha_d^T + h(P_1^d \alpha_{ed}^V + P_2^d \alpha_{ed}^T)]$$

$$\sigma(h,\, P_1^d,\, P_2^d) = \sigma_0[1 + P_1^d \alpha_d^V + P_2^d \alpha_d^T + h(P_1^d \alpha_{ed}^V + P_2^d \alpha_{ed}^T)]$$

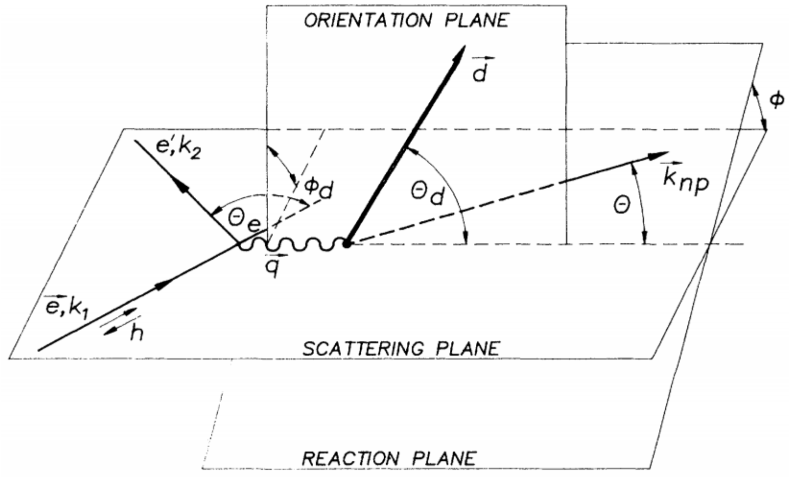
0 0 0

$$\alpha_d^V(\theta_d, \phi_d) = \frac{1}{2P_1^d \sigma_0}[\sigma(0,\, P_1^d,\, P_2^d) - \sigma(0,\, -P_1^d,\, P_2^d)]$$
$$= \frac{6c}{\sigma_0}\rho_{LT} F_{LT}^{1-1} \sin \phi_d d_{-10}^1(\theta_d) \ ,$$

0 0

$$\alpha_{ed}^T(\theta_d, \phi_d) = \frac{1}{4hP_2^d \sigma_0}[\sigma(h, P_1^d, P_2^d) - \sigma(-h, P_1^d, P_2^d) + \sigma(h, -P_1^d, P_2^d) - \sigma(-h, -P_1^d, P_2^d)]$$
$$= \frac{6c}{\sigma_0}\rho'_{LT} F_{LT}^{\prime 2-1} \sin \phi_d d_{-10}^2(\theta_d) \ .$$

0 0



W Leidemann, *et al*, PRC **43**, 1022 (1991)

$$\sigma = \sigma_0[1 + P_2^d \alpha_d^T] = \sigma_0[1 + P_{zz} A_{zz}]$$

Polarization Cycle

Each polarization cycle is an independent measurement of A_{zz}

- Annealing and target motion only at the start of a new cycle
- Any issues from annealing or material shifts will be isolated to a single cycle
  - Dilution/packing fraction runs at the beginning and end of each cycle can recover data surrounding a material shift event
- Doubled the number of cycles for the lowest Q^2 measurement